

WAVE EROSION OF AN UNPROTECTED
FROZEN GRAVEL BERM

FINAL REPORT

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1. INTRODUCTION

As oil resources are developed nearshore along the Arctic coastline, coastal installations are being constructed as bases for production. In shallow waters, these installations are typically gravel structures interconnected by causeways. In more temperate zones, these structures would be protected from wave erosion by some form of slope protection. But in the Arctic, the cost of fabricating and installing slope protection is so high that the cost of the slope protection can potentially equal the cost of the base structure. Therefore, it is economically desirable to forego the slope protection if the risk of wave erosion is not excessive. To date, many slopes have been left unarmored for this reason with hopes that a catastrophic failure will not occur.

The assessment of risk of wave erosion is nontrivial because of a lack of information in many areas, two of which are:

1. The resilience of a frozen sediment layer to wave impingement is totally unknown.
2. Natural erosion rates of gravel slopes is not well known.

The former area is particularly difficult to assess for several reasons. First, it may be that the thermal gradient between the open water and the frozen berm is small enough that only minor surface melting occurs. The thermal core therefore could resist erosion over typical storm durations. Second, the thermal melting rate may be great enough that it matches or exceeds the natural erosion rate of a steep unfrozen gravel slope. In this case, there would be no difference in the erosion process between a frozen or unfrozen slope. Third, the unfrozen interconnected voids in a frozen berm may allow pore water migration within the berm with each passing wave. Internal melting of the slope could occur, potentially causing a calving of pieces of the slope due to the wave action.

Until the actual erosion mechanism is understood, a justifiable rationale for whether to apply slope protection cannot be made. The decision has tremendous economic as well as environmental implications. The following study presents the results of a simple wave erosion test of an unarmored frozen gravel berm. Based on the results, some preliminary assessments about the erosion process and the need for slope protection are made.

2. OBJECTIVE

The overall objective of this study was to assess the viability of deleting slope protection from Arctic frozen gravel berms which are subject to wave attack. To accomplish this, the following specific objectives were defined:

1. Establish the slope erosion rate for a typical Beaufort Sea wave condition.
2. Establish the freeze front location with time.
3. Define the equilibrium beach profile for a frozen and nonfrozen gravel slope.

The method of approach was to create a prototype size model of a frozen berm and subject it to wave attack. The erosion of the slope and the melting process was then physically monitored, and the results were used to determine the need for slope protection for the conditions tested.

3. METHOD OF APPROACH

To define a comparative erosion rate for a frozen gravel berm, an actual erosion rate for an unfrozen berm had to also be established. Therefore, two series of tests were conducted, the first with a frozen berm and the second with an unfrozen berm. The two erosion rates and processes were then compared to establish both the relative and absolute degradation of each.

3.1 Frozen Berm Modeling

3.1.1 Construction

Correct melting at the frozen interface is the most crucial aspect of the study program. To best examine the phenomena it was judged preferable to perform a physical model study in prototype scale. This offered several advantages:

- Prototype scale gravel could be used rather than sand. This eliminates scale effects in the slope profile equilibrium and melting processes.
- Voids between stones would be properly sized, thus allowing for correct exchange of pore water.
- The melting rate could be examined in relation to mechanical removal of slope material.

A two-dimensional gravel berm was constructed at one end of the ARCTEC COAST facility. The ARCTEC COAST facility is a wave tank which measures 100 ft by 12 ft by 6 ft. The tank is enclosed in a refrigerated room allowing the simulation of wave attack on a frozen berm. The construction of the frozen berm is depicted in Figure 3.1. The berm was built to a 1:3 slope using lifts of gravel, approximately 0.5 feet thick. After placement of a lift of gravel, the berm was sprayed with a fine cold mist of water until it became fully frozen. Each lift took approximately two days to complete, with the gravel already cooled to the ambient temperature of $(-)2^{\circ}\text{C}$. The final product was a homogeneous non-layered, monolythic structure.

For this pilot project freshwater was used both in the misting of the berm layers and in the wave tank. This was primarily due to a desire to make the thermal and mechanical properties of the simulated frozen berm as uniform as possible. This eliminated the possibility of having unfrozen brine pockets occurring inside the berm which could cause uneven melting or eroding. Although this is a real phenomena in the field, it introduces added complexity to the study. Numerical analyses of frozen soils also ignore brine pocket formation.

Three-eighths inch pea gravel (size range 5/8- to 1/8-inch) was used to construct the berm. This size of material corresponded to the median gravel size and shape for construction gravels used in the Prudhoe Bay area. An actual distribution from the ARCO Putuligayuk River quarry site is shown in Figure 3.2. For the pea gravel mix used, the porosity was determined to be 42 percent. Because of the method of construction, 100 percent saturation can be assumed.

3.1.2 Temperature Monitoring

During berm construction a matrix of thermocouples was embedded in the gravel. The thermocouples used have reported accuracies of 0.5°C. The definition of the freeze front is, therefore, only determined within that accuracy. A 1-foot horizontal spacing and 0.5-foot vertical spacing was used to form the thermocouple matrix. The shallowest thermocouples were roughly 1-foot beneath the gravel surface. The relative thermocouple positions are shown in Figure 3.3.

3.1.3 Test Conditions

Prototype scale waves were directed against the berm in a water depth of 2.79 feet. The wave period used was 5 seconds, and wave heights, prior to breaking on the slope, were measured to be 1.4 feet. Significant wave heights and periods in this range are typical of annual storms in the Arctic. To keep analysis simple only regular waves were used. Throughout the test program the water temperature was held constant at 0.60°C and air temperature remained at 4.4°C.

3.1.4 Data Sampling

The data collection effort consisted of: periodic slope surveying and berm temperature monitoring. Temperatures within the berm were monitored and manually recorded every fifteen minutes. The eroded slope was surveyed every half hour. A video record of the test was made to aid in subsequent analysis of the erosion process.

3.2 Unfrozen Berm Modeling

Upon completion of the frozen berm tests, the berm was allowed to thaw. The berm slope was then groomed to re-establish a simple 1:3 slope. The erosion test was then repeated using the same wave conditions. The erosion rate was measured initially every 5 minutes until the rate declined. Later in the test measurements were made every half hour.

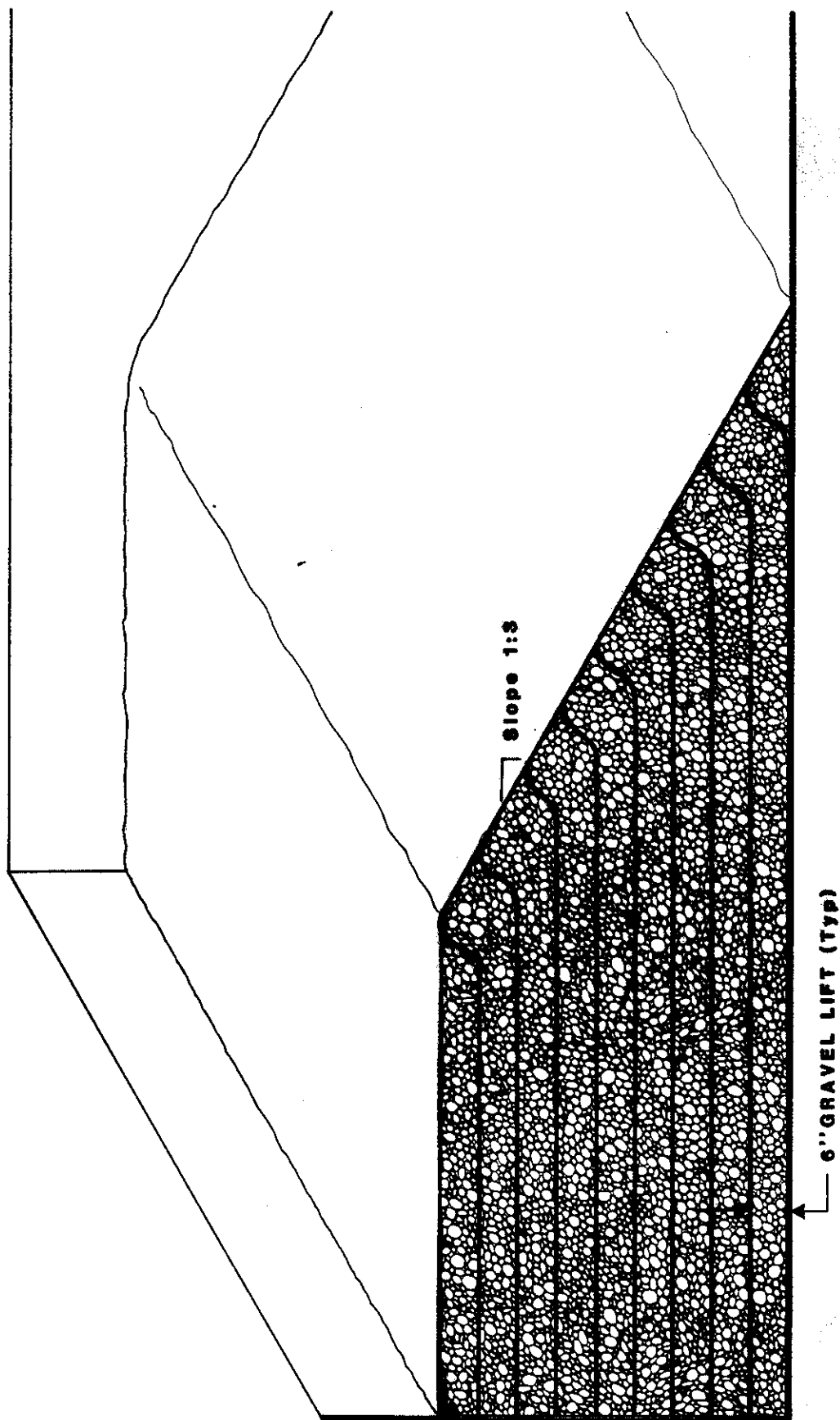


Figure 3.1
CONSTRUCTION OF FROZEN BERM IN COAST FACILITY

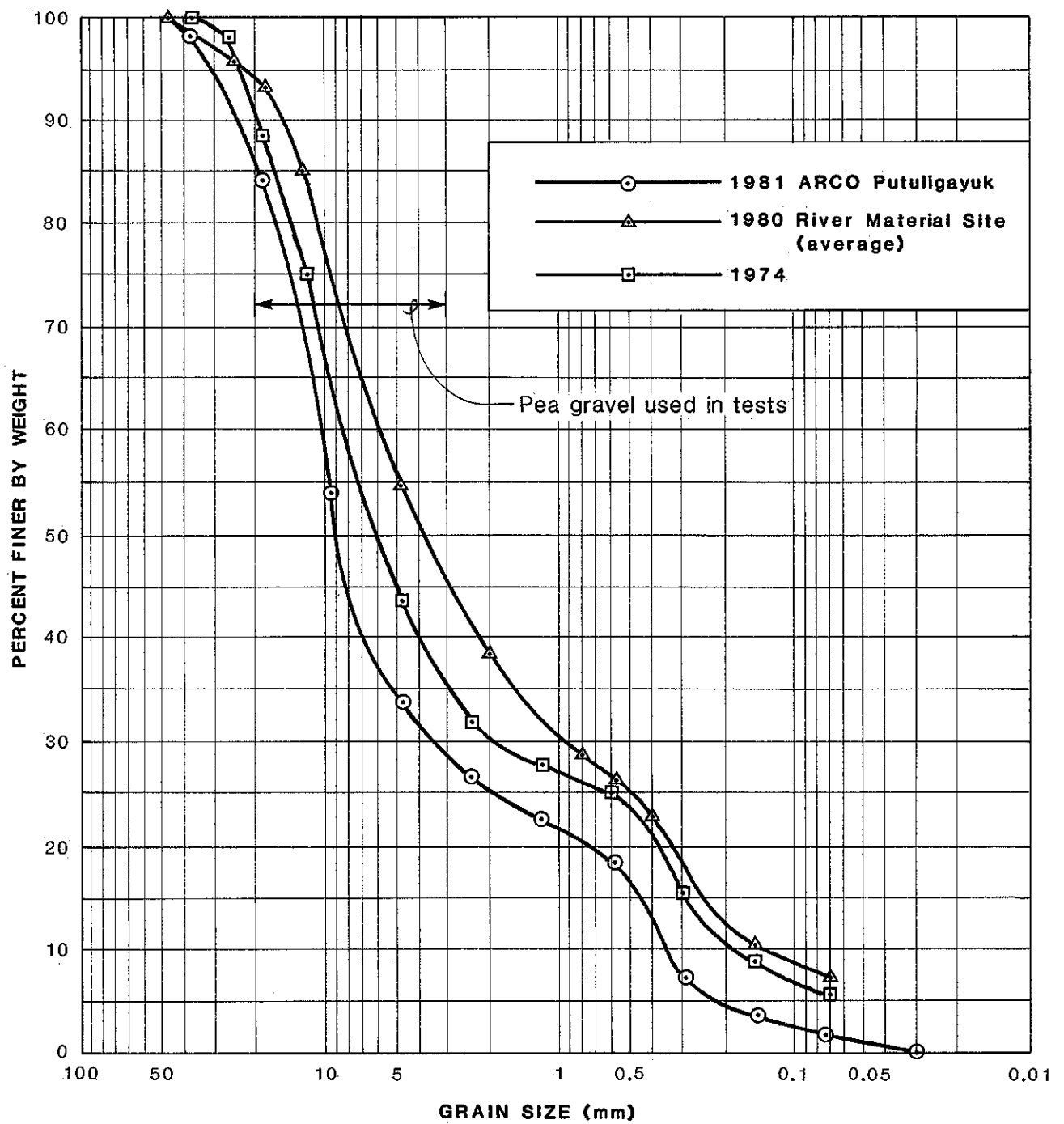


Figure 3.2
TYPICAL BERM GRAVEL SIZE DISTRIBUTION

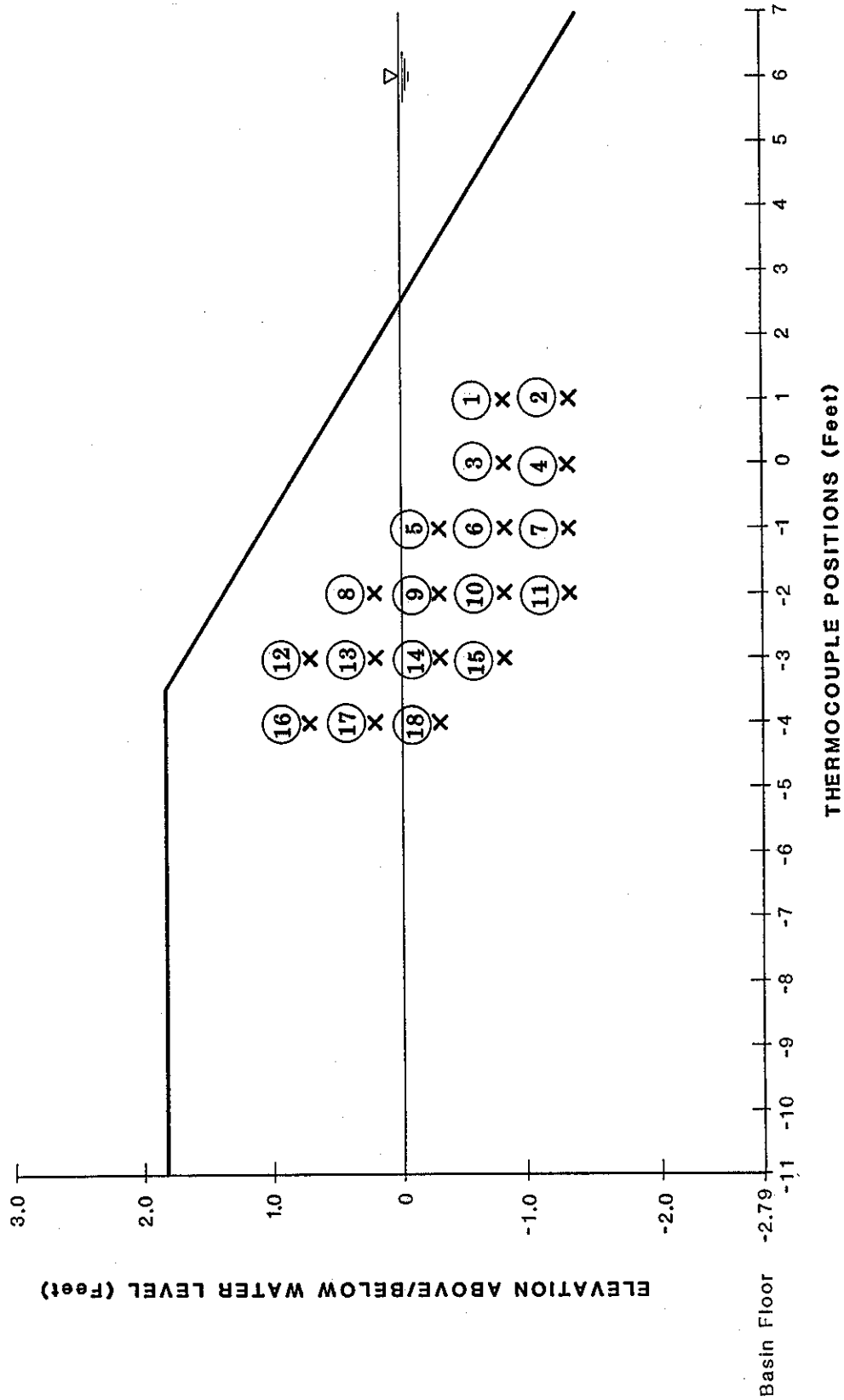


Figure 3.3
THERMOCOUPLE LOCATIONS INSIDE BERM

4. TEST RESULTS

4.1 Frozen Berm

4.1.1 Erosion Rate

The test of the frozen berm spanned a 24-hour period. This period was broken into three segments: 12 hours, 8 hours, and 4 hours. Because the test was purely two-dimensional, eroded slope material could not be carried away by longshore current. This meant that eroded material could potentially remain on the slope, thereby mechanically and thermally protecting the frozen berm from further erosion. Kobayashi and Aktan (1984) explored this possibility numerically and suggest several orders of magnitude reduction in erosion rate if the gravel remains. To explore what effect longshore current removal of sediment might have on the erosion process, at the end of each segment the slope was raked clean of any unfrozen gravel. This re-exposed the frozen core to direct wave attack. The test was then reinitiated to monitor a change in erosion rate for the clean slope.

Figures 4.1, 4.2 and 4.3 show the change in slope over time. Note that the majority of erosion occurs in the first test segment and is limited to the (-)0.7 ft elevation and above. The attack is just below the waterline, carving a bench into the slope. The limit of this erosion roughly coincides with the depth of a wave trough. The eroded material appears to deposit down slope at elevation (-)1.0 to (-)1.5 ft, extending the bench. It is not clear whether this bench was a transitional or equilibrium feature. The angle of the beach slope at the waterline appears to pivot about the (-)0.7 ft level. The slope changed from 1:3 to 1:8 on the forming bench.

For the later test segments when the bench of loose gravel was raked away, only very minor changes in the down slope geometry occurred. Below the depth of one wave height the slopes remained 1:3, apparently unaffected by wave attack. The trend to reshape the slope continued only at the waterline.

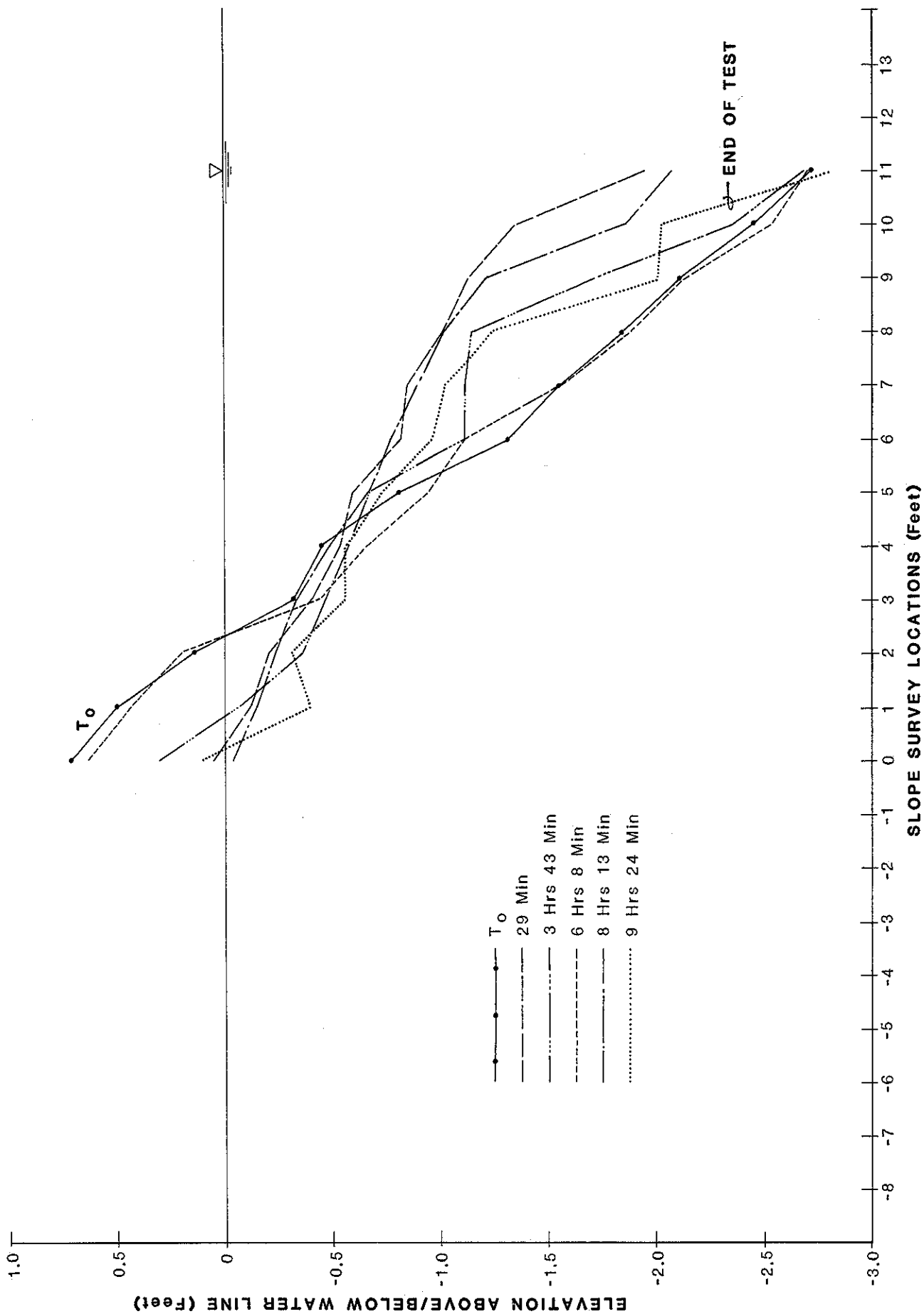


Figure 4.1
CHANGE IN ERODED SLOPE PROFILE
(FROZEN TEST SEGMENT 1)

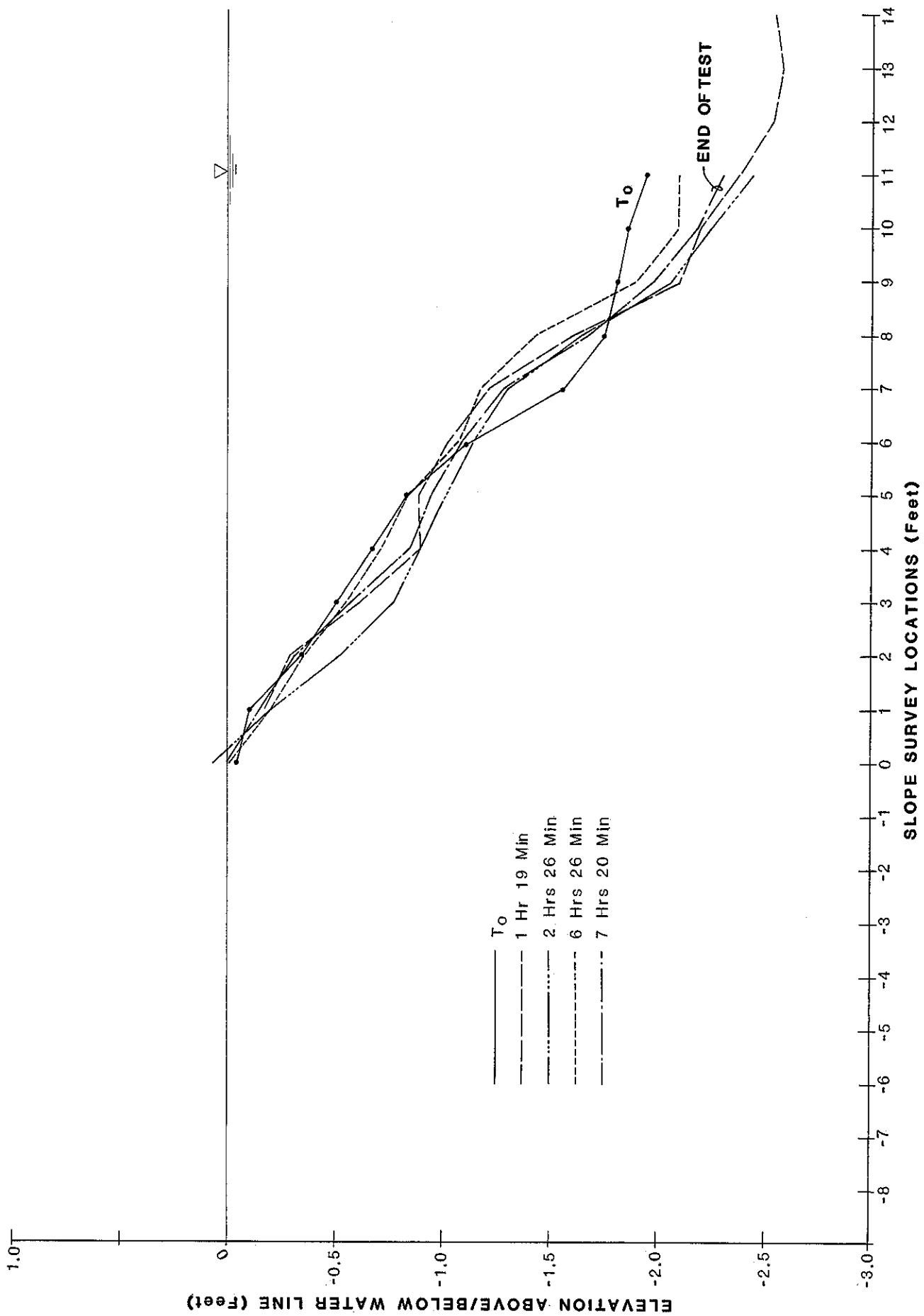


Figure 4.2
CHANGE IN ERODED SLOPE PROFILE
(FROZEN TEST SEGMENT 2)

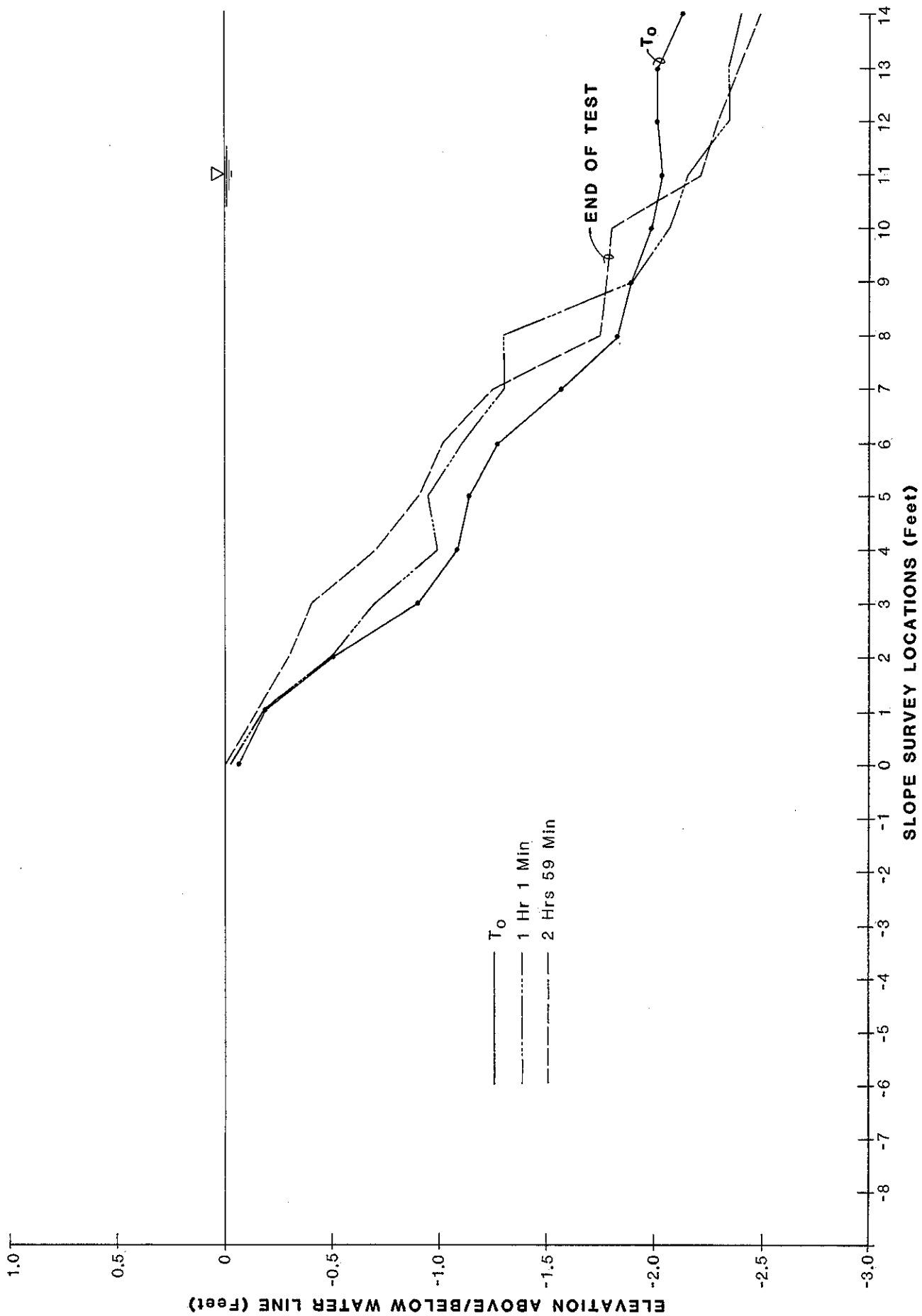


Figure 4.3
CHANGE IN ERODED SLOPE PROFILE
(FROZEN TEST SEGMENT 3)

4.1.2 Temperature Change

Figures 4.4 through 4.17 show temperature distributions throughout the berm as a function of time relative to the position of the eroded face. All temperatures are reported in degrees centigrade to facilitate locating the freeze front. Note that there is no strongly ascertainable developing temperature gradient through the berm. Rather, the thermocouples reveal an almost uniform warming in the outer 2 feet of gravel. The exceptions are those thermocouples (No. 5, 8, 13) which reflect the nearness of the eroding surface. Whatever temperature gradient exists apparently occurs at an interval smaller than the thermocouple array size of 0.5-foot vertical by 1-foot horizontal.

Also note in Test Segments 2 and 3, removal of unfrozen gravel protecting the frozen slope does not appear to accelerate the rate of melting.

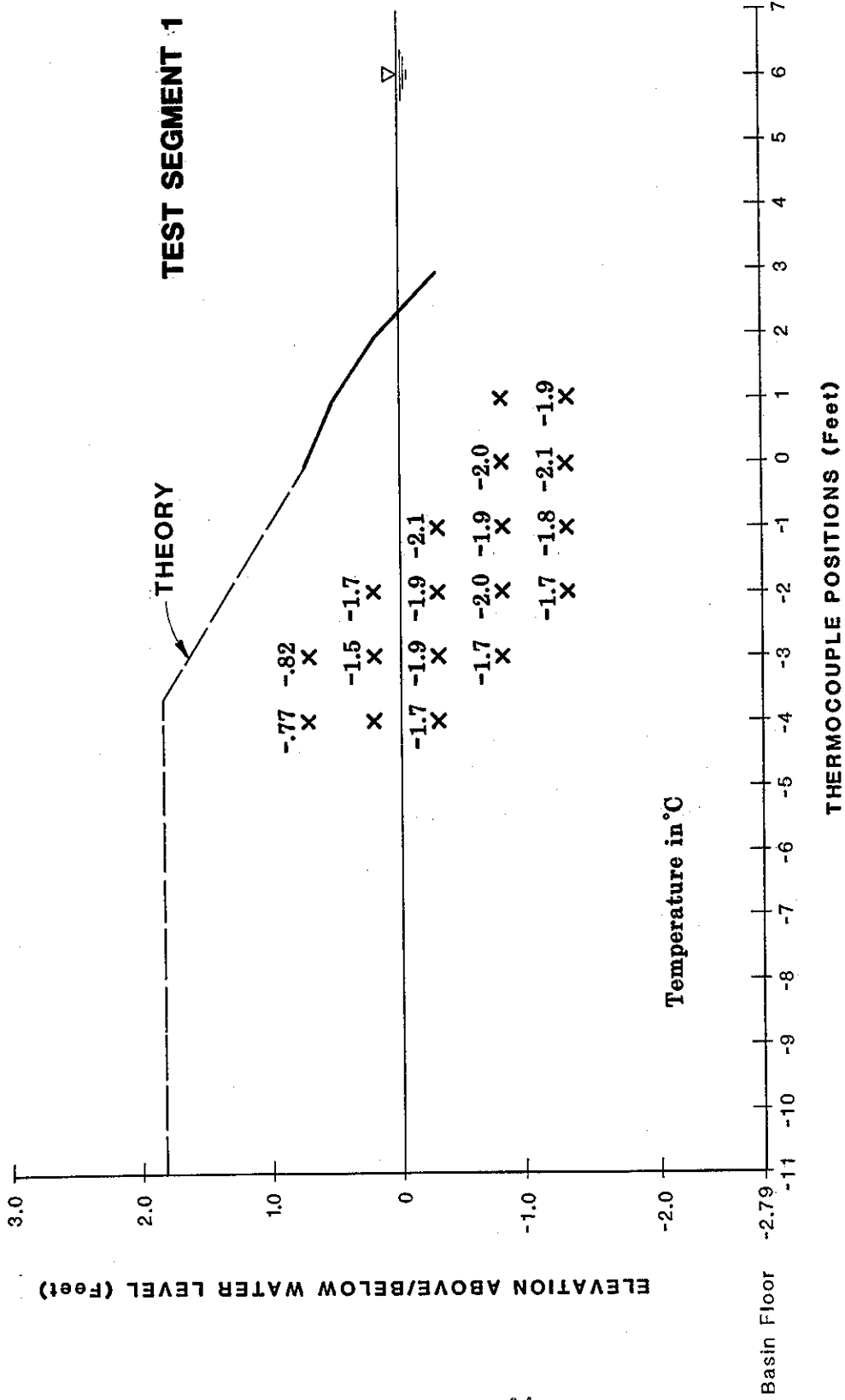


Figure 4.4
TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT Time T₀

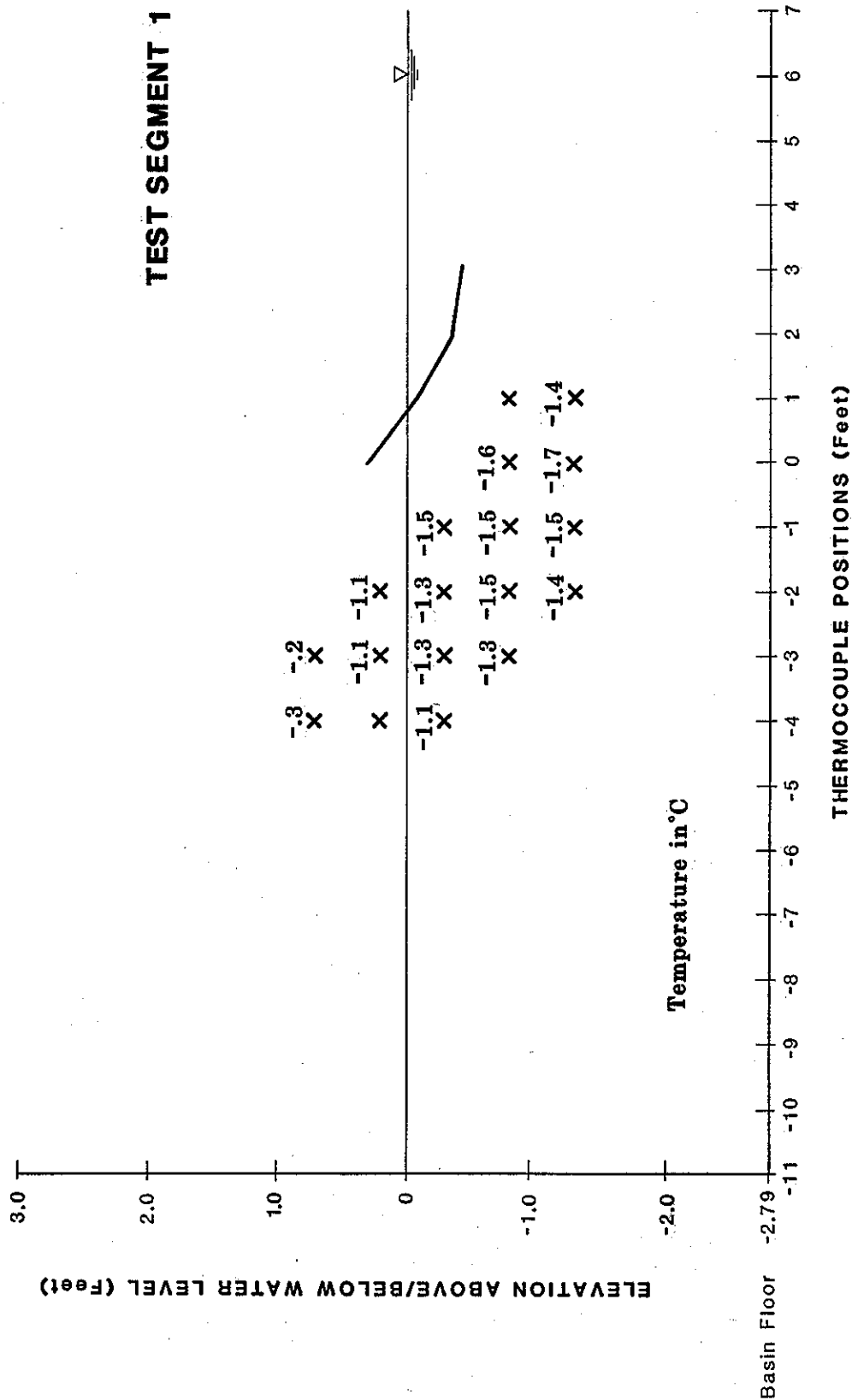


Figure 4.5

TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT: Time 3hrs 43min

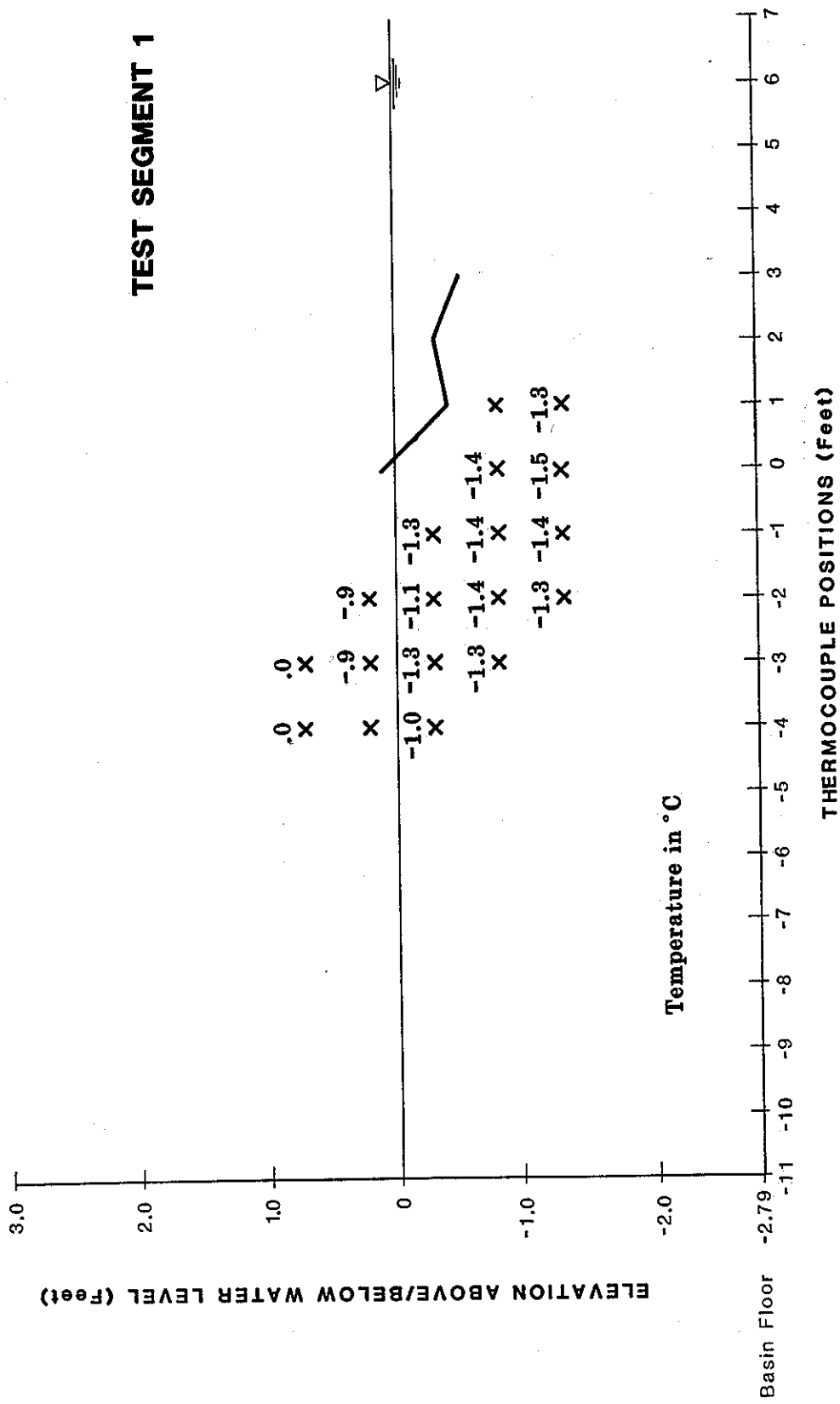
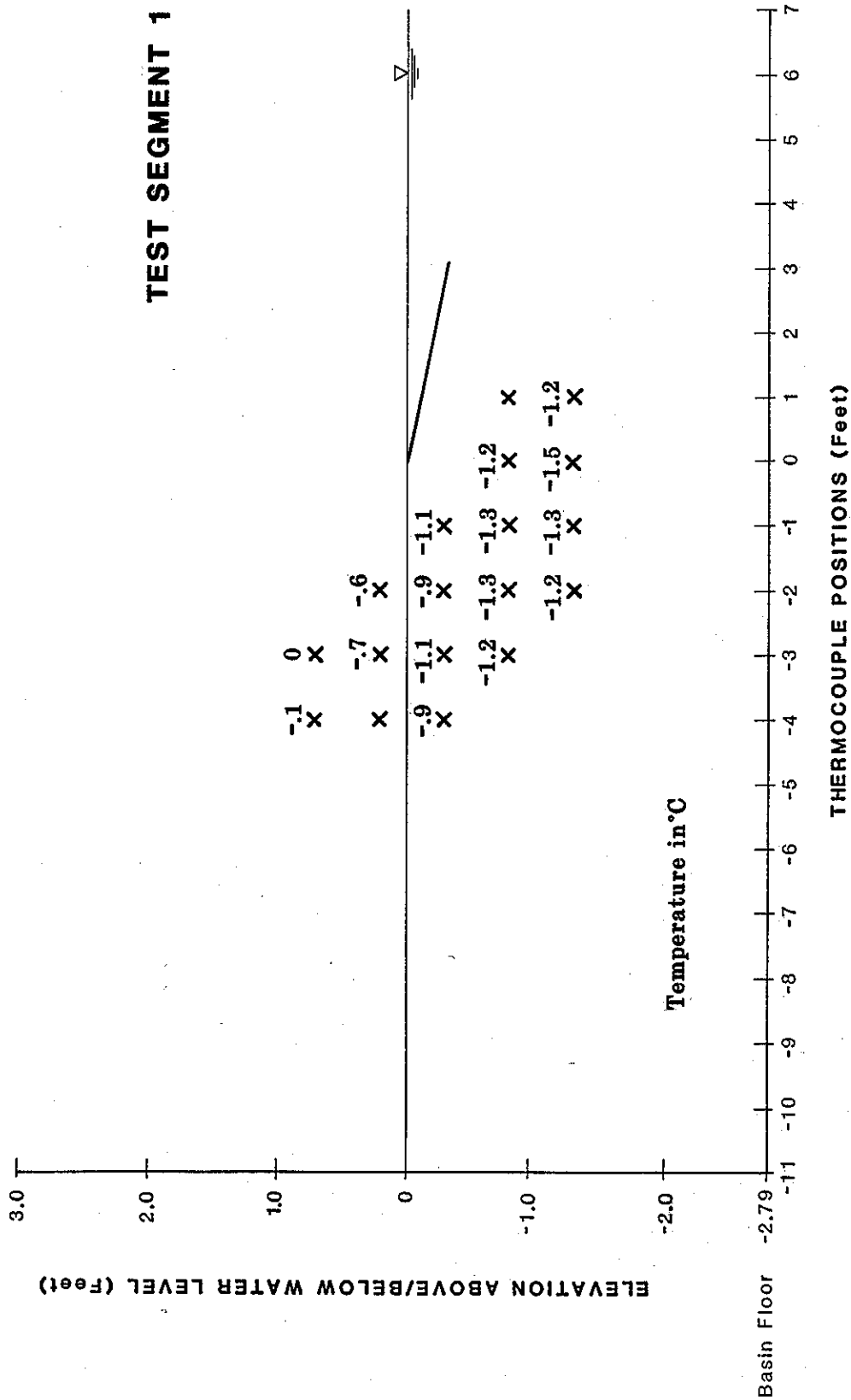


Figure 4.6

TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT : Time 6hrs 5min



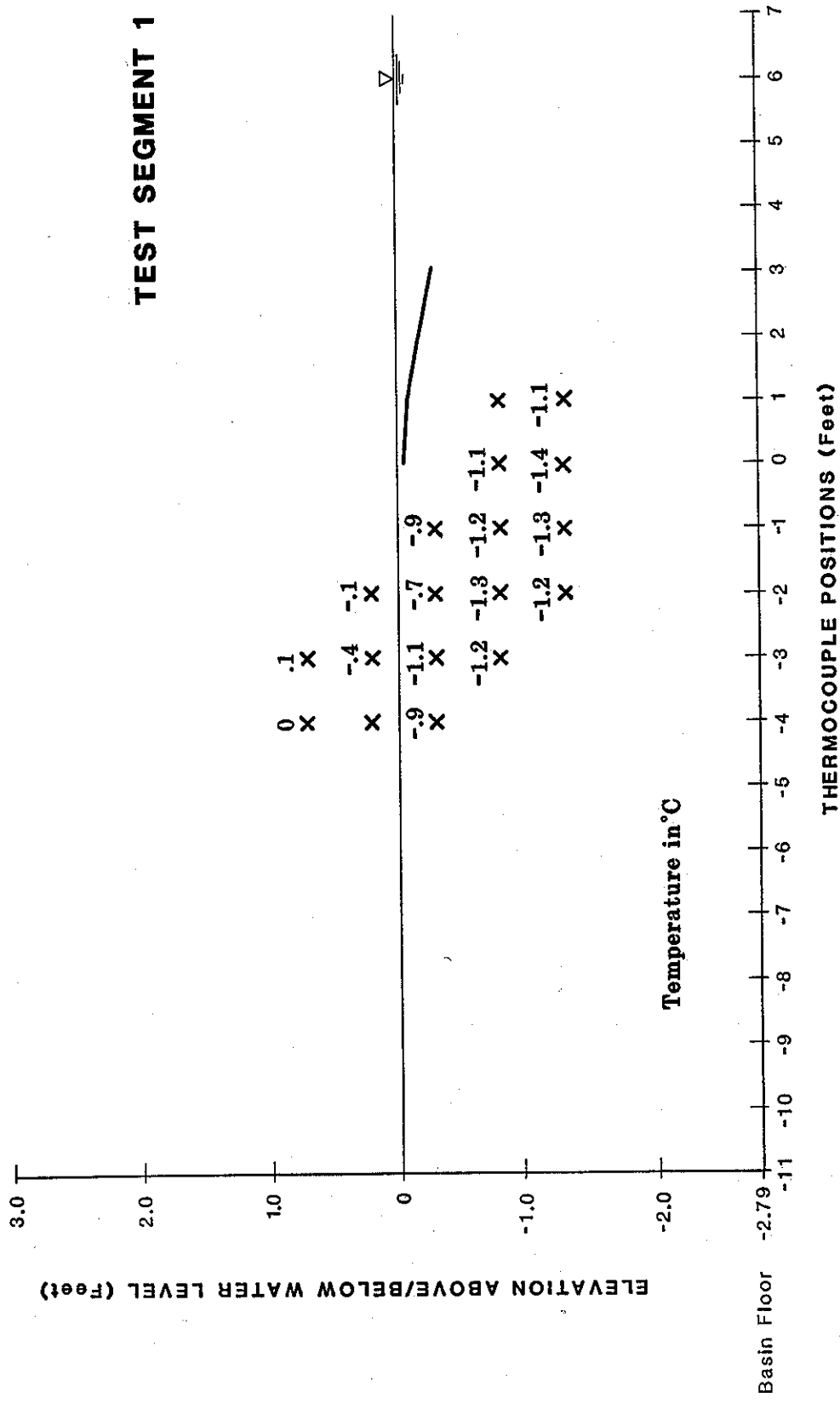


Figure 4.8

TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT: Time 10hrs 57min

ELEVATION ABOVE/BELOW WATER LEVEL (Feet)

TEST SEGMENT 2

Temperature in °C

THERMOCOUPLE POSITIONS (Feet)

Thermocouple Position (Feet)	Approximate Temperature (°C)
.3	-4.0
.3	-3.8
.1	-2.5
.1	-2.2
-.6	-4.0
-.6	-3.8
-.7	-2.5
-.7	-2.2
-.8	-3.8
-.8	-3.5
-.9	-2.5
-.9	-2.2
-1.0	-2.5
-1.0	-2.2
-1.0	-1.8
-1.0	-1.5
-1.0	-1.2
-1.0	-1.0
-1.1	-3.8
-1.1	-3.5
-1.1	-2.5
-1.1	-2.2
-1.1	-1.8
-1.1	-1.5
-1.1	-1.2
-1.1	-1.0
-1.2	-2.5
-1.2	-2.2
-1.2	-1.8
-1.2	-1.5
-1.2	-1.2
-1.2	-1.0

Figure 4.9
TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT TIME T₀

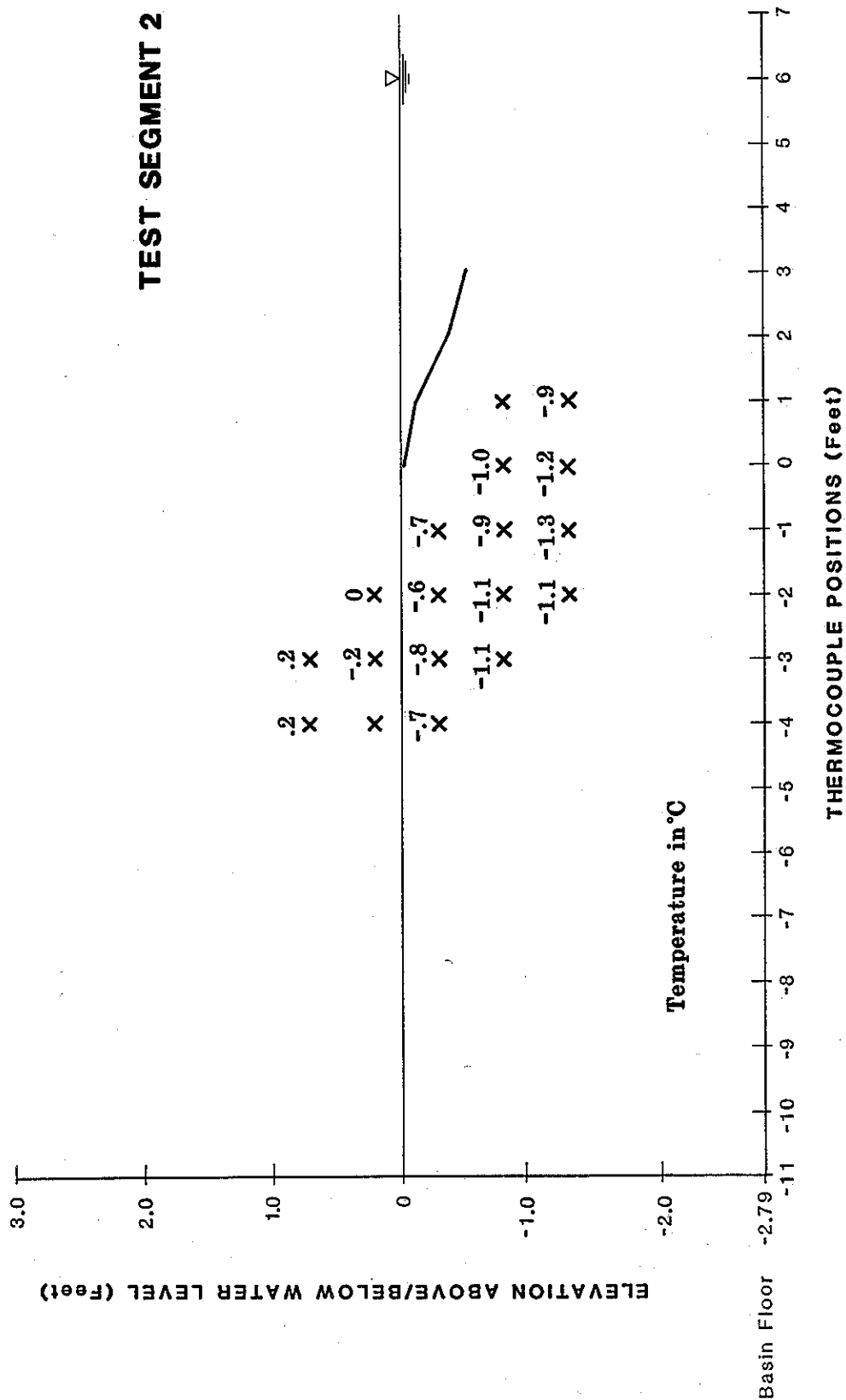


Figure 4.10
TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT :Time 44min

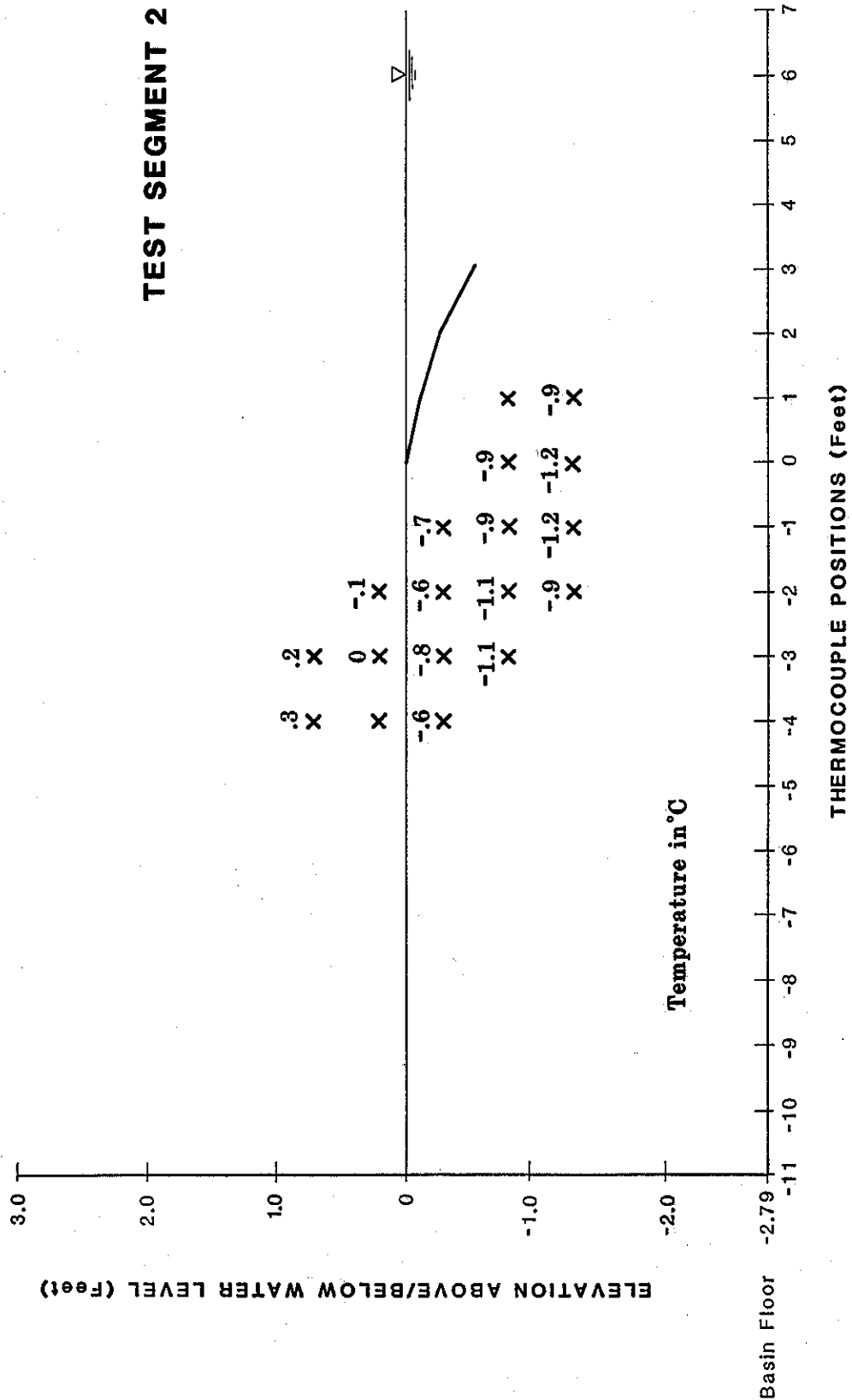


Figure 4.11

TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT:Time 2hrs 26min

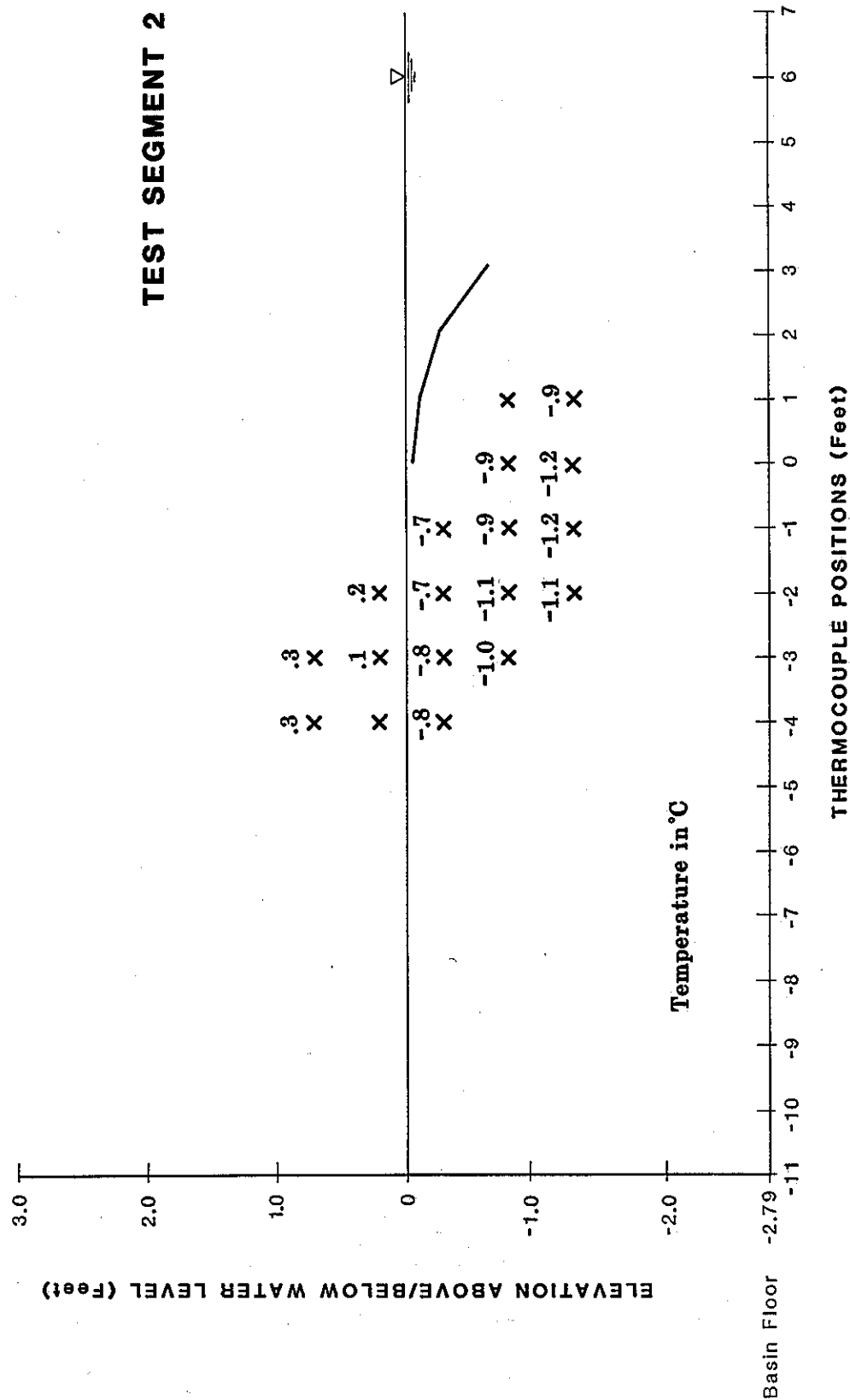


Figure 4.12

TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT :Time 4hrs 32min

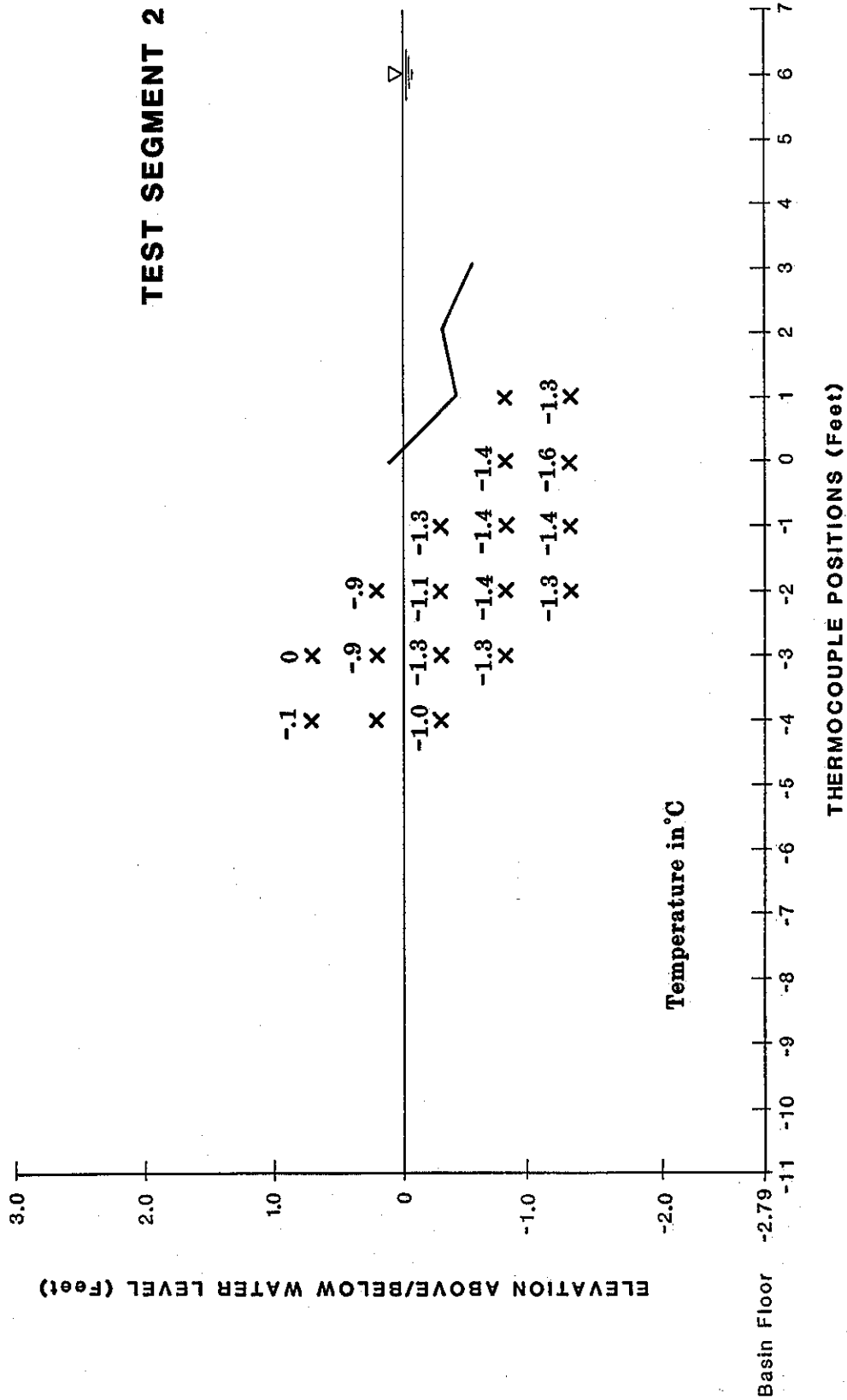


Figure 4.13

TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT : Time 6hrs 8min

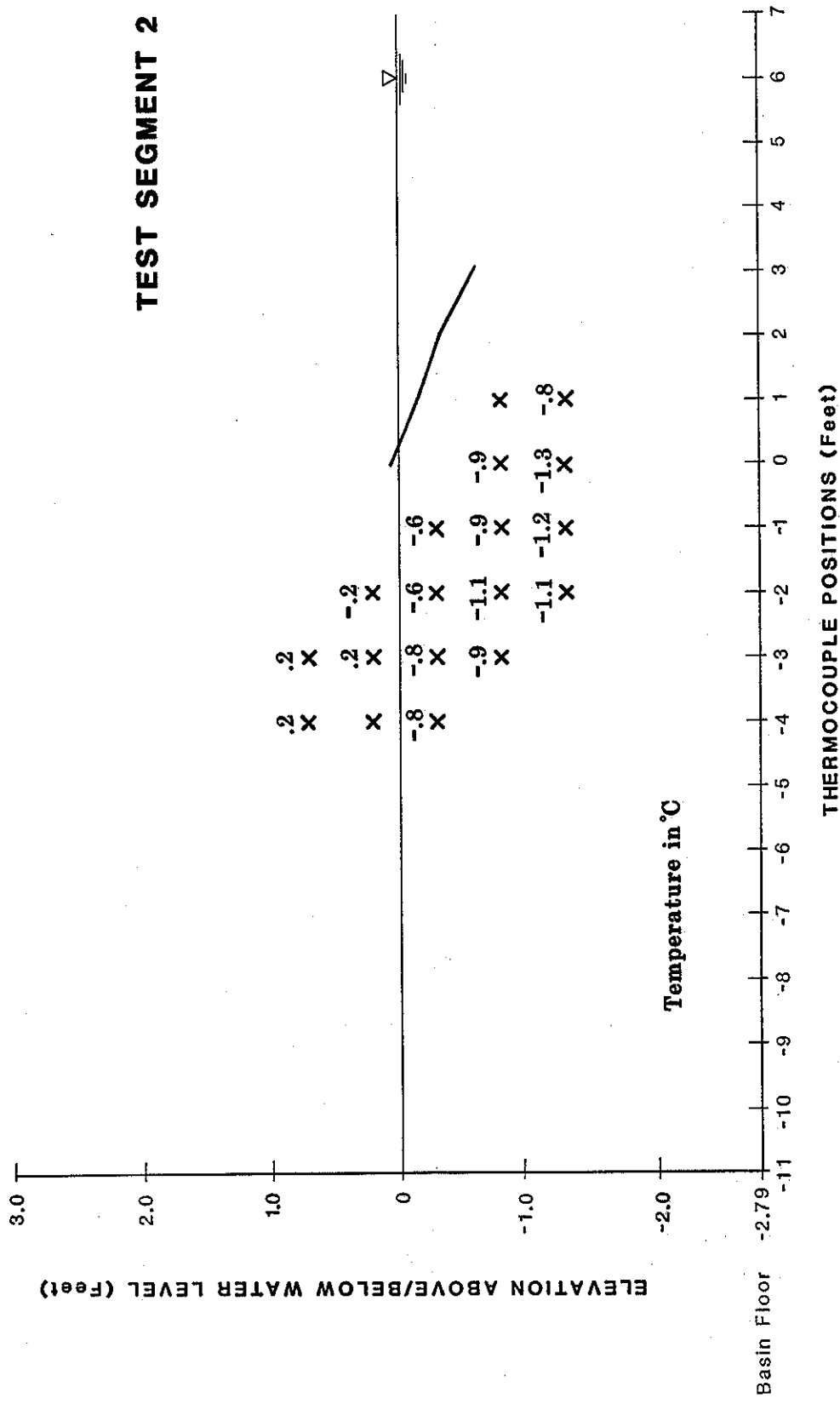


Figure 4.14

TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT : Time 7hrs 20min

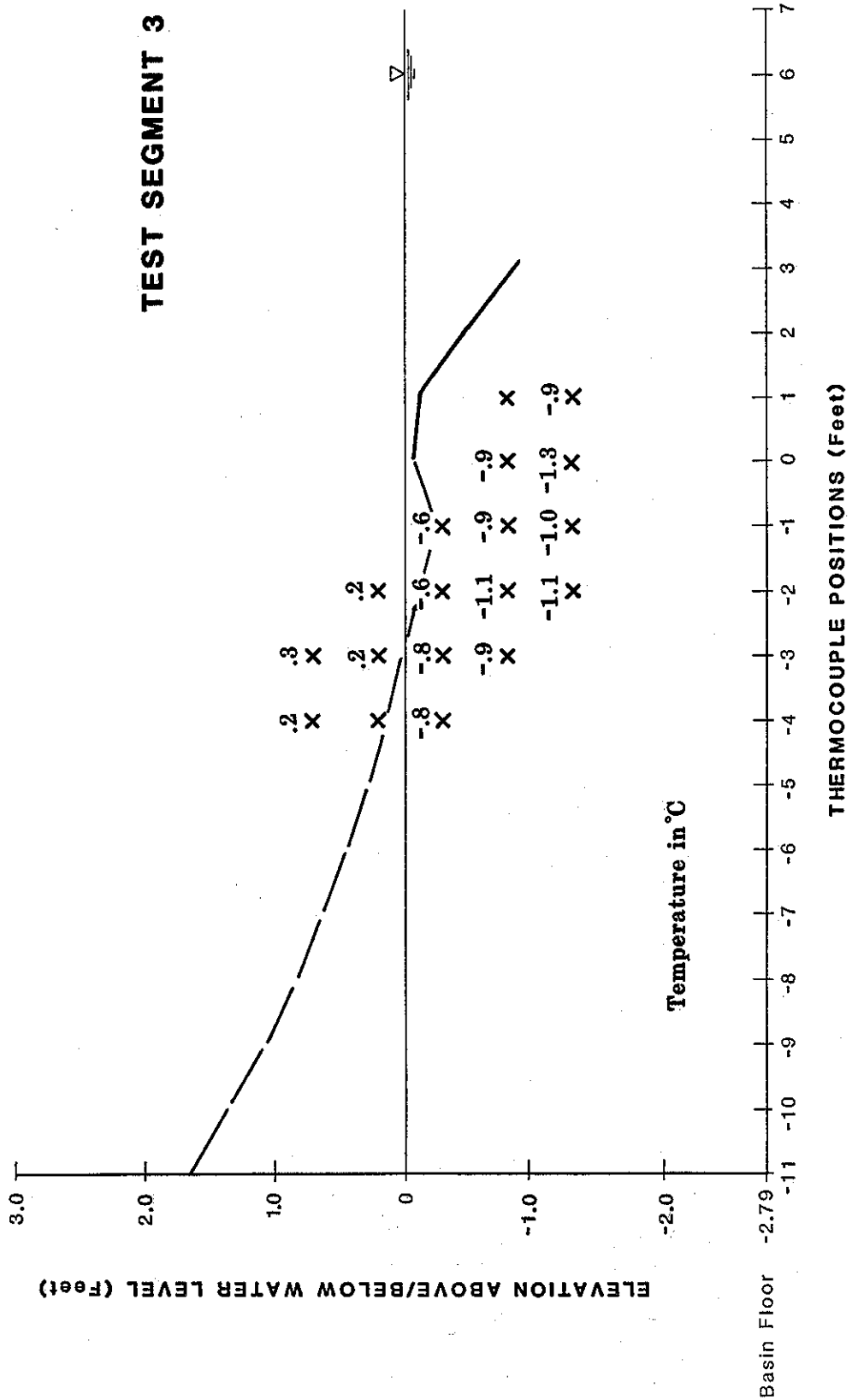


Figure 4.15

TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT : Time T₀

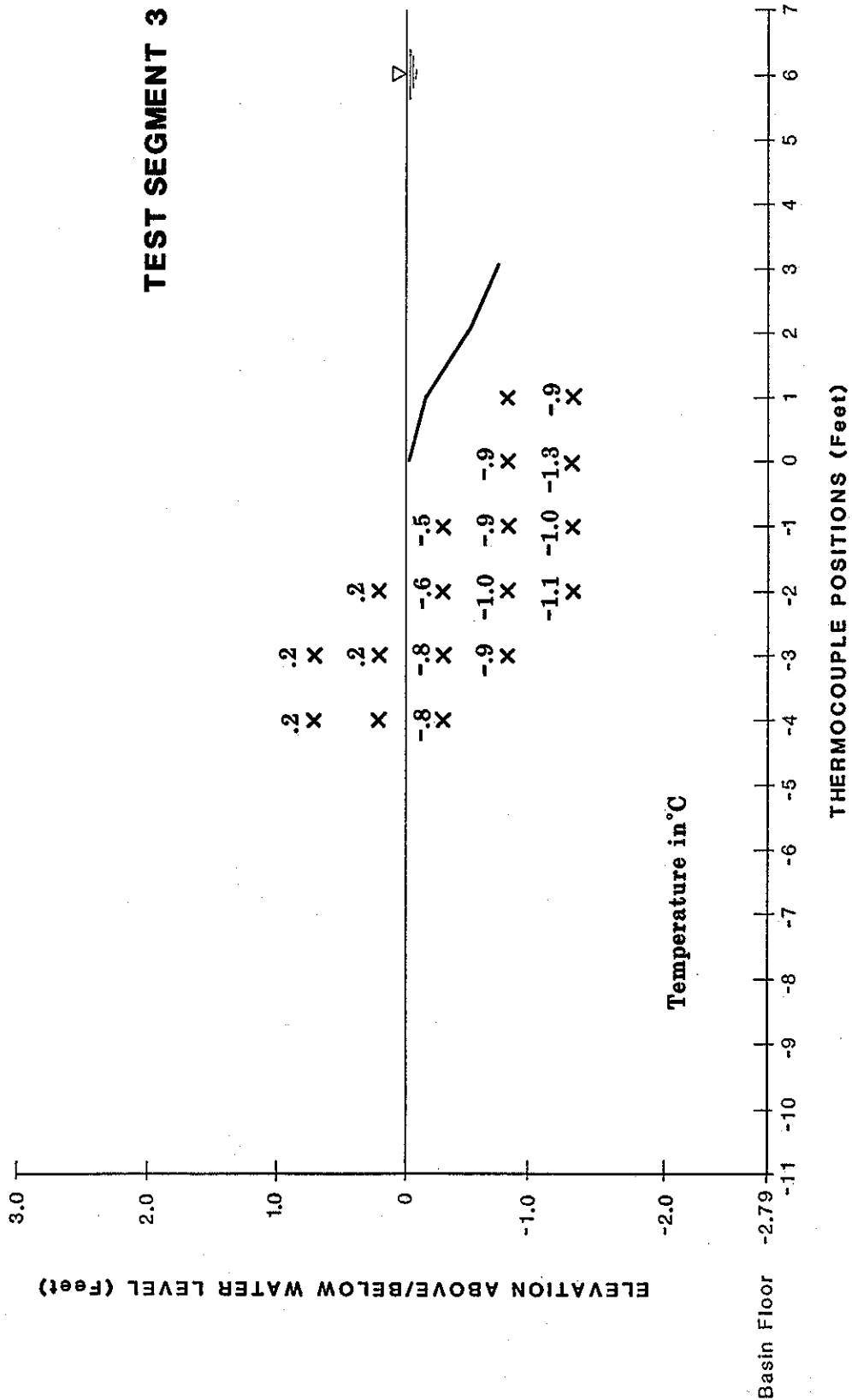


Figure 4.16

TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT : Time 1hr 1min

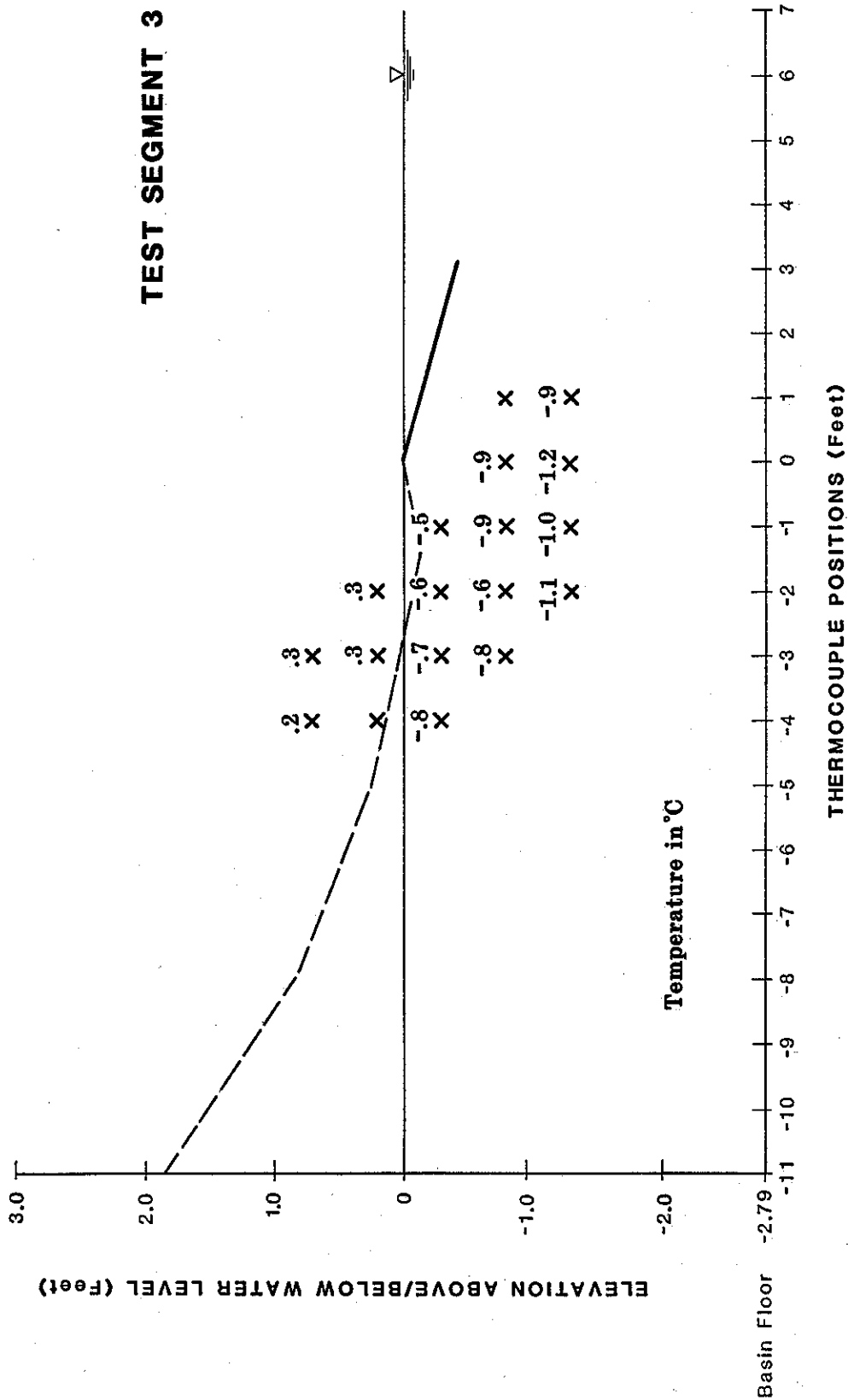


Figure 4.17

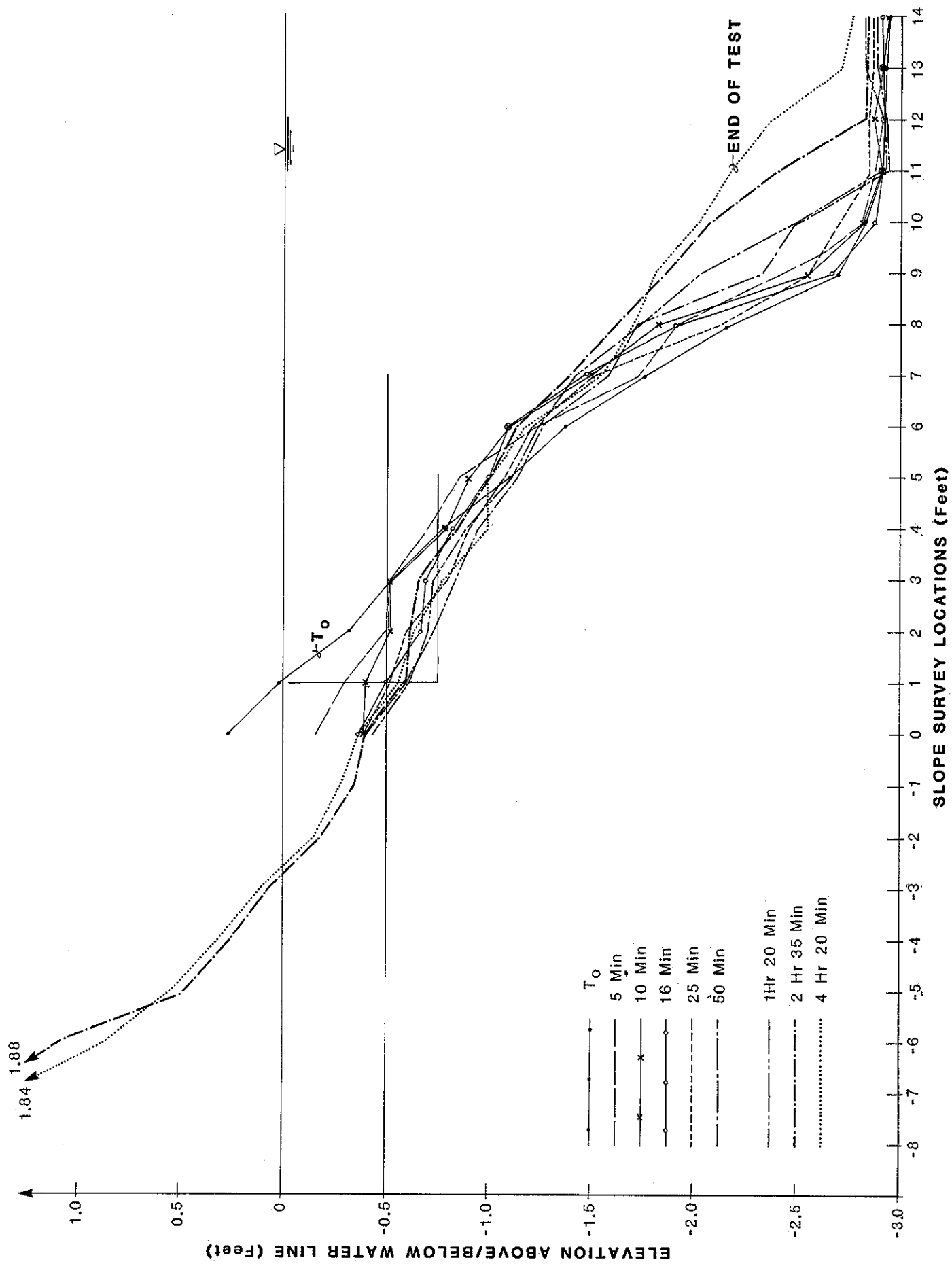
TEMPERATURE DISTRIBUTION AND EROSION SURFACE LOCATION AT : Time 2hrs 59min

4.2 Unfrozen Berm

4.2.1 Erosion Rate

In contrast to the frozen berm, the erosion of unfrozen gravel developed very rapidly. Figure 4.18 shows the transformation of the slope with time. The area of erosion is above (-)1.0 ft. The equilibrium slope angle pivots about that point changing from a 1:3 slope to a 1:7 slope.

The gravel movement down slope differed from the frozen case. In the frozen case the deposit remains higher on the slope, building seaward and creating a bench. In the unfrozen case, the material does not remain high on the slope but rather accumulates continuously to the floor. In addition, much of the eroded material appears to be carried up slope with the wave runup. No bench feature was observed developing as in the frozen berm case.



**Figure 4.18 CHANGE IN ERODED SLOPE PROFILE
(UNFROZEN BERM)**

5. ANALYSIS OF RESULTS

5.1 Frozen Berm

5.1.1 Physical Interpretation

The vertical, horizontal and volumetric erosion rates measured at 0.3 ft below the still water level are presented in Figure 5.1. The erosion rate appears to be essentially a constant 0.4 ft/hour for the first five to six hours of wave attack. The rate then appears to fall off. This apparent reduction in erosion rate is believed to be the product of deposition of eroded upslope material. The plot shows the location of the gravel surface and not necessarily the location of the frozen interface.

Sunamura (1973) proposed a mechanism for the cycling erosion rate over time. Slope instability produced by wave erosion at the waterline causes slumping of unsupported upslope material. This renders the slope more stable by reducing the slope angle, and simultaneously supplies protective debris to the waterline. Once waves remove this debris the slope can again be undercut, creating a circular erosion relationship. This phenomena of cycling between gentle and steep slopes is depicted in Figure 5.2.

Using the six hour erosion process as a basis, the erosion rate of the frozen face in the horizontal direction appears to be approximately 0.4 feet per hour.

Figure 5.3 presents a time history of temperature within the berm. Note Thermocouples 3 and 5, which are deeper in the berm, show essentially the same temperatures while Thermocouples 8 and 12, which are nearer to the surface and above the still waterline, are warmer. All of the thermocouples show essentially the same relative temperature change over time, demonstrating the uniform warming of the berm. The dip in temperature between Hours 2 and 3 is explained by a change in the reference temperature. True temperature rose uniformly at a rate of 0.29°C an hour.

The trace for Thermocouple 12 suggests that the frozen interface passed the location of Thermocouple 12 approximately six hours into the test. Based on its physical position inside the berm, this roughly corresponds to the time when the eroded surface, as determined by survey, also reached this point. A similar conclusion can be made with the coincident timing of freeze front location and eroded surface for Thermocouple 8. It therefore appears that for the single example studied, i.e., frozen freshwater-filled pea gravel at 1:3 slope, the freeze front advances with the eroded face position. In other words, any thawed sediment is immediately removed from the waterline by onshore-offshore transport mechanisms.

The analysis of Test Segments 2 and 3, depicted in Figures 5.4. and 5.5, suggest that very little continued erosion occurred in these tests. Since the tests were reinitialized by removing any loose sediment from the surface, this might appear contradictory with the results of the first

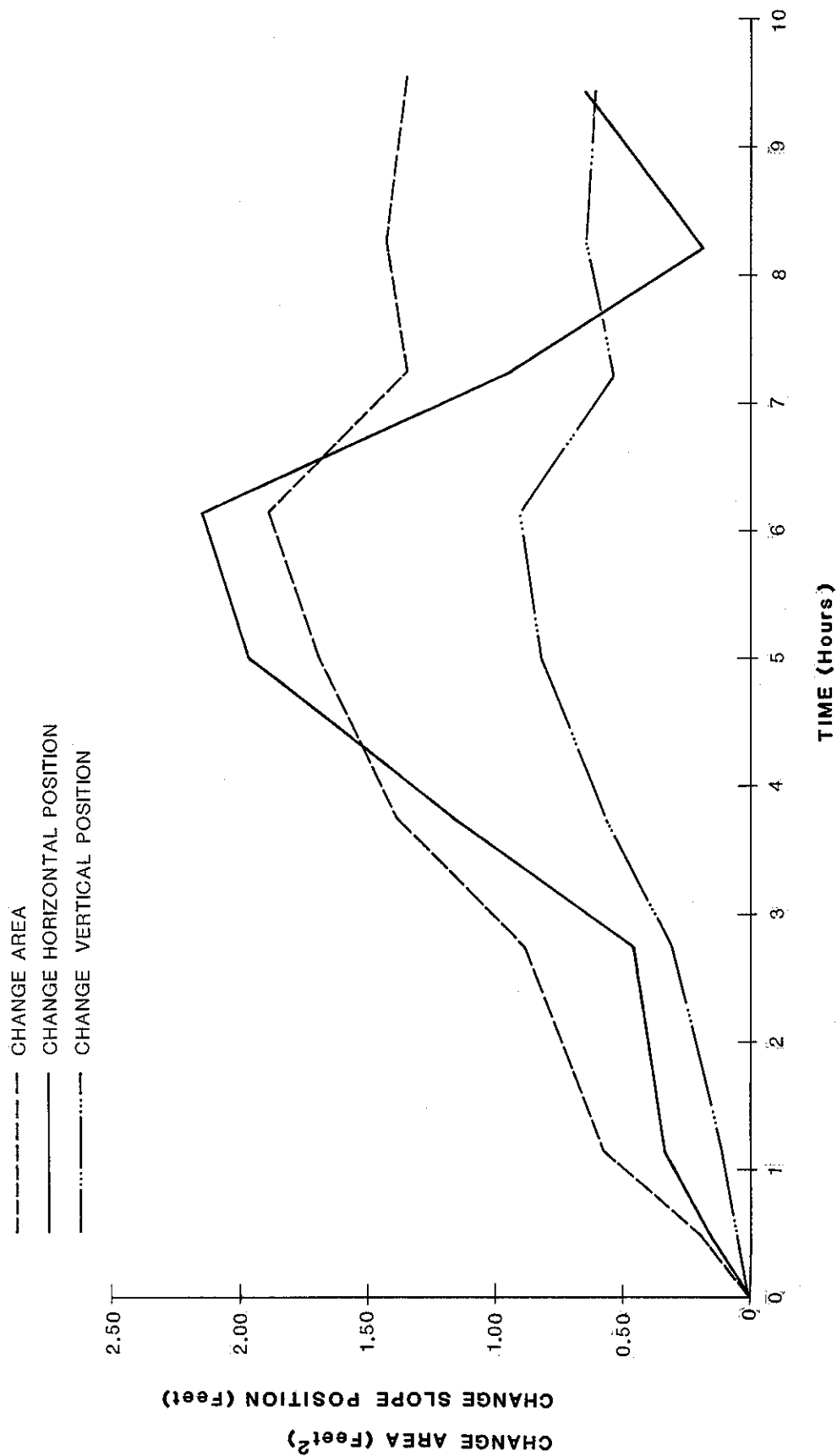


Figure 5.1
CHANGE IN AREA AND SLOPE DISPLACEMENT WITH TIME
(MEASURED AT EL.-0.3 Ft) TEST SEGMENT 1

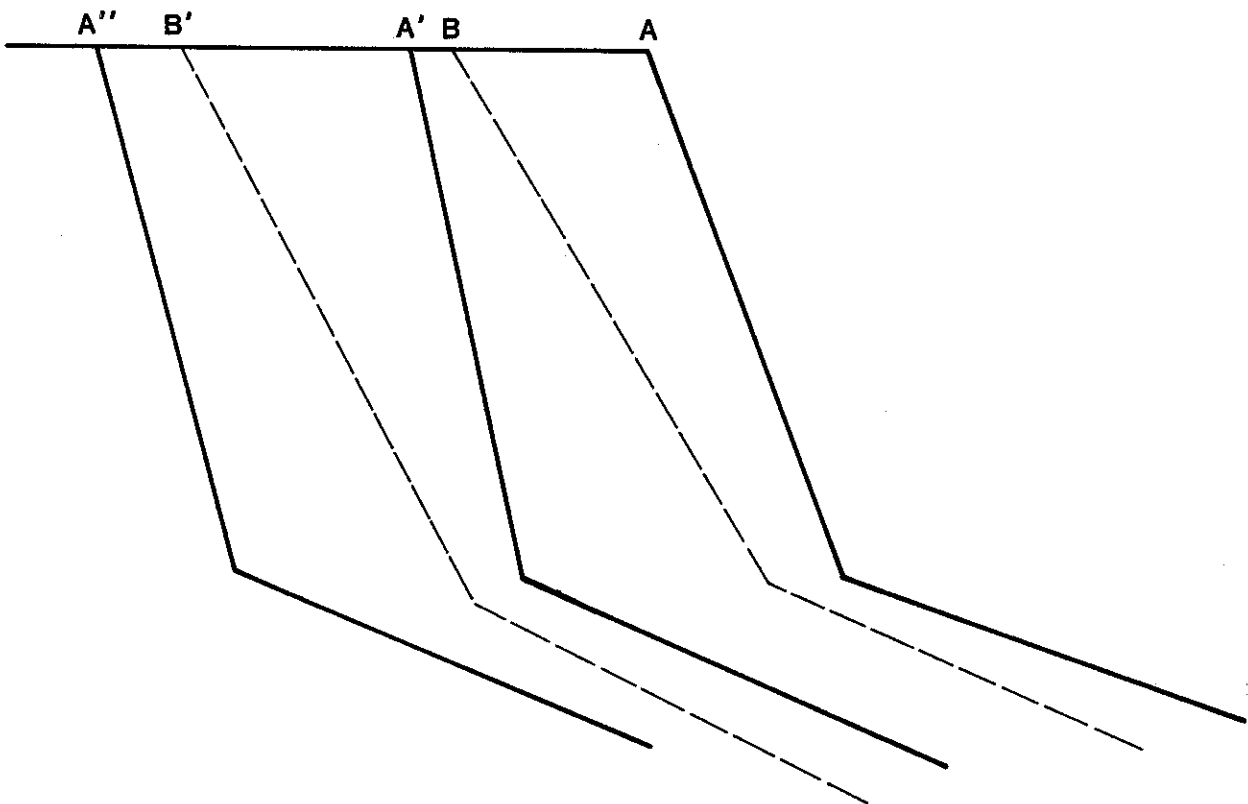


Figure 5.2
SCHEMATIC DIAGRAM SHOWING CLIFF RECESSION
WITH AN ALTERNATING STEEP AND GENTLE SLOPE
(SUNAMURA, 1973)

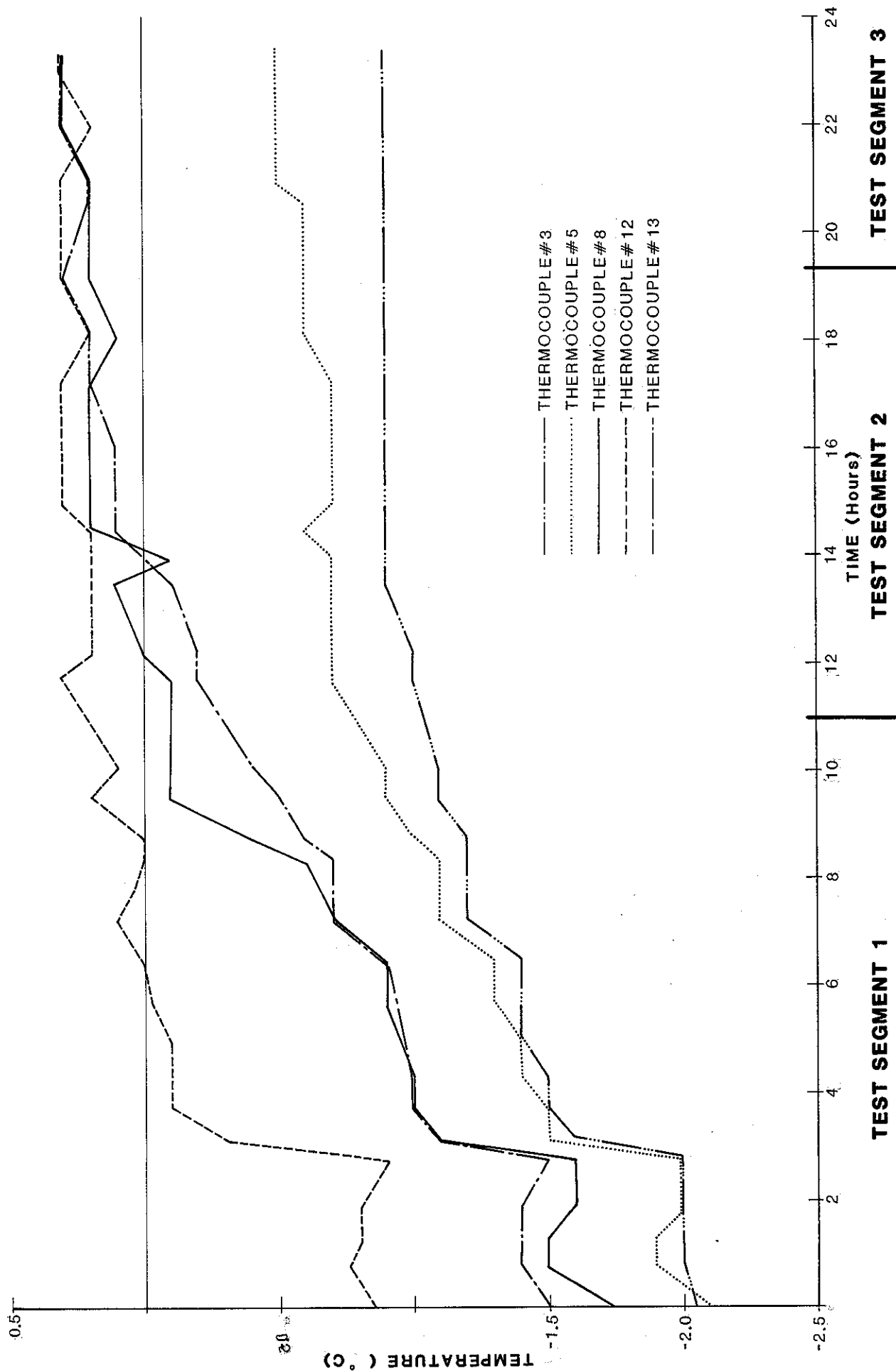


Figure 5.3
CHANGE IN BERM INTERNAL TEMPERATURE WITH TIME

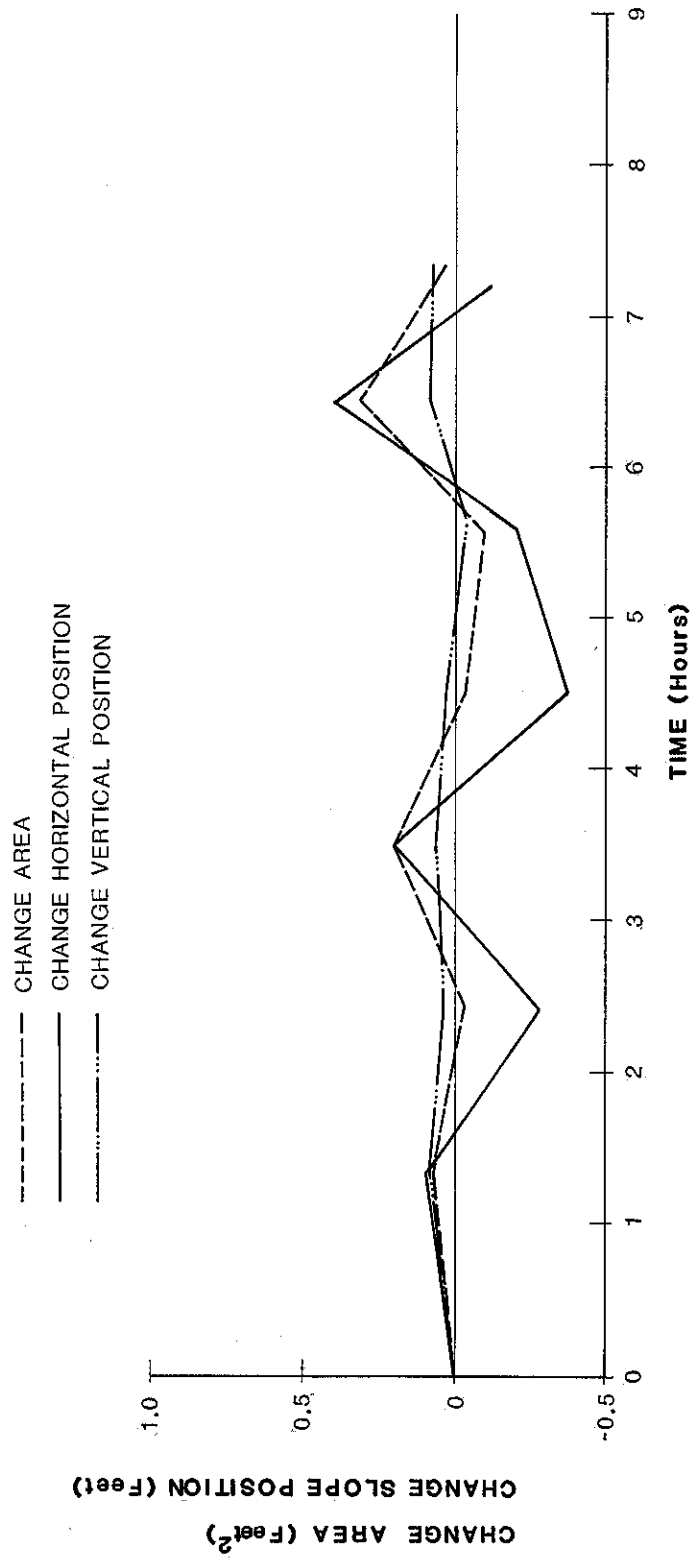


Figure 5.4
CHANGE IN AREA AND SLOPE DISPLACEMENT WITH TIME
(MEASURED AT EL.-0.3 Ft) TEST SEGMENT 2

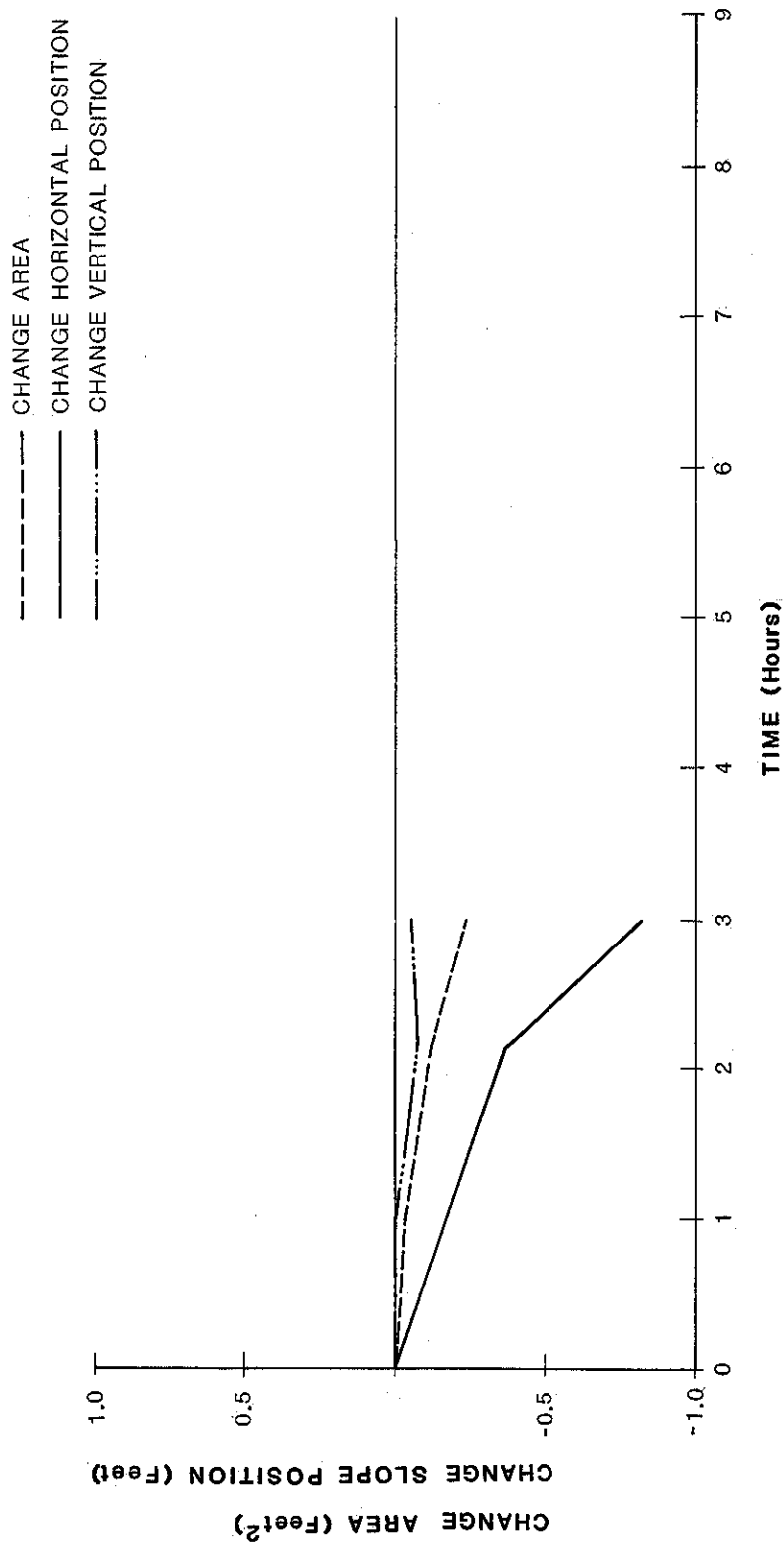


Figure 5.5
CHANGE IN AREA AND SLOPE DISPLACEMENT WITH TIME
(MEASURED AT EL.-0.3 Ft) TEST SEGMENT 3

test segment. The results, however, present only the slope response at 0.5 ft below the waterline. In reality, erosion is continuing as revealed by the thermocouples but it is occurring at the waterline or above. The apparent erosion mechanism is thawing only in the zone of direct wave attack. Left long enough the anticipated product of wave attack on the frozen berm would be the creation of a frozen "bench" submerged at a depth of one wave height. Armored breakwaters which have been degraded above the water line by wave action also tend to re-establish an equilibrium shape one wave height below still water level. This contrasts significantly with the results of the unfrozen berm discussed in the next section.

5.1.2 Theoretical Interpretation

A theoretical thermal erosion rate can be computed at the berm surface assuming that all gravel is removed by wave action as it thaws. The governing one-dimensional heat conduction equation is written as:

$$C_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (k_s \frac{\partial T}{\partial x})$$

in which C_s is the volumetric heat capacity of the frozen sediment and k_s is the thermal conductivity of the sediment. The boundary conditions at the melting surface may be expressed as:

$$T = T_m, \text{ at } x = s$$

and

$$L \frac{ds}{dt} = h_w (T_w - T_m) + k_s \frac{\partial T}{\partial x}, \text{ at } x = s$$

where h_w is the convective heat transfer coefficient associated with the flow of water, T_w is the ambient water temperature, s is the location of the melting surface, and L is the latent heat of fusion of the frozen sediment. If a constant rate of heat flux, $h_w (T_w - T_m)$, is maintained into the frozen sediment, the amount of heat influx in the time interval $[0, t]$ can be expressed as

$$h_w (T_w - T_m) t = Ls + \int_0^s C_s (T_m - T_0) dx + \int_0^\infty (T - T_0) dx$$

where T_0 is the initial frozen berm temperature. The sum of the first and second terms on the right hand side expresses the amount of heat required to melt the frozen sediment which is then immediately removed. The third term expresses the amount of heat used to increase the temperature of the frozen sediment from T_0 to $T < T_m$. The characteristic migration velocity of the melting surface is given as (Kobayashi and Aktan, 1984):

$$\dot{s} = \frac{h_w (T_w - T_m)}{L (1 + \epsilon)}$$

where

$$\epsilon = \frac{C_s (T_m - T_0)}{L}$$

The two heat coefficients, h_w and L , must be related to the physics of the problem. For a frozen sediment the latent heat is given as (Johnston, 1981):

$$L = 143.4 S n \gamma_w \text{ (BTU/ft}^3\text{)}$$

where S is degree of saturation, n is porosity, and γ_w is specific gravity of water. For 100 percent saturation and a porosity of 42 percent, $L = 3.76 \cdot 10^3 \text{ BTU/ft}^3$.

The convective heat transfer coefficient must be related to flow and sediment characteristics. A definition of the coefficient under oscillatory flow conditions, such as wave motion, does not exist. However, if heat transfer in a turbulent boundary layer over a flat plate is considered analogous, then h_w associated with oscillatory flow might tentatively be expressed as (Kobayashi and Aktan, 1984):

$$h_w = \frac{1/2 f_w C_w U_b}{1 + \sqrt{1/2 f_w E}}$$

with

$$E = 5 (P - 1 + 2n [1 + 5/6 (P-1)]) \quad \text{for } \left[\frac{U_* k_s}{\nu} < s \right]$$

and

$$E = 0.52 \left[\frac{U_* k_s}{\nu} \right]^{0.45} P^{0.8} \quad \text{for } \left[\frac{U_* k_s}{\nu} > 70 \right]$$

In this expression f_w is the friction factor at the melting surface, C_w is the volumetric heat capacity of the fluid, U_b is the representative fluid velocity immediately outside the boundary layer, P is the Prandtl number $= (\nu C_w / k_w)$, where ν is the kinematic viscosity of the fluid, k_w is the thermal conductivity of the fluid, k_s is the equivalent sand roughness of the surface, and U_* is the shear velocity associated with the shear stress at the melting surface $= (\sqrt{1/2 f_w} U_b)$. The expression for E is dependent on whether the turbulent boundary layer flow is hydraulically smooth or rough (Schlichting, 1968).

The representative fluid velocity is hardest to characterize because the wave is in the process of breaking on the slope. The breaking wave form which occurs on a 1:3 slope can be characterized as plunging to surging. Miller and Zeigler (1964) have observed that velocity profiles in this type of breaker tend to be uniform over depth and equal to the wave speed at breaking. U_b can therefore be considered equal to $\sqrt{g(\eta + d_b)}$ where η is crest height and d_b is water depth at breaking. Because of the steep slope, the wave motion becomes almost purely translational and the wave form approaches solitary. Therefore, the wave essentially becomes a bore moving upslope such that η is approximately the total wave height. Near the water line d_b is very small so that $U_b \approx \sqrt{gH}$. For this test $H \approx 1.4 \text{ ft}$ which suggests that $U_b \approx 6.7 \text{ ft/sec}$.

Therefore, given the following properties (Johnston, 1981)

$$C_S = 52.2 \text{ BTU } (^\circ\text{C} \cdot \text{ft}^3)$$

$$k_S = 3.2 \text{ BTU}/(^\circ\text{C} \cdot \text{ft} \cdot \text{hr}) \quad (\text{soil 100\% saturated, porosity 42\%})$$

$$L = 3.76 \cdot 10^3 \text{ BTU}/\text{ft}^3 \quad (\text{soil 100\% saturated, porosity 42\%})$$

$$T_W = 0.4^\circ\text{C}$$

$$T_m = 0^\circ\text{C}$$

$$T_O = (-) 1.8^\circ\text{C}$$

$$v = 1.92 \cdot 10^{-5} \text{ ft}^2/\text{sec}$$

$$C_W = 11.52 \text{ BTU}/(^\circ\text{C} \cdot \text{ft}^3)$$

$$k_W = 0.59 \text{ BTU}/(^\circ\text{C} \cdot \text{ft})$$

$$f_W = 0.02 \text{ (Jonhson, 1966)}$$

The convective heat transfer coefficient for the case considered can be determined to be:

$$h_W \approx 4.1 \cdot 10^3 \text{ BTU}/(^\circ\text{C} \cdot \text{ft}^2 \cdot \text{hr})$$

The melting rate of the surface, s , then becomes 0.42 ft/hr in the horizontal direction. This agrees very closely with the observed erosion rate in the wave tank test up to the time when loose debris begins to protect the waterline from further erosion. It also indicates that the erosion rate is totally controlled by the melting process and that the freeze front does not propagate ahead of the erosion front.

5.2 Unfrozen Berm

5.2.1 Physical Interpretation

The unfrozen gravel berm adjusts to its equilibrium slope very rapidly. Figure 5.6 shows the movement of the slope and change in area at the waterline. Note that after the first fifteen minutes the slope has essentially stabilized, the rate of erosion advance appears to be approximately 4.5 ft/hour with a 1.4 foot impinging wave. This rate is nearly ten times that of the frozen case. Perhaps more significant, however, is that the entire slope adjusts to the wave attack (Figure 4.18), not simply the zone about the waterline as in the frozen case (Figure 4.1). Whereas in the frozen case, erosion only occurred where heat exchange was substantial, (i.e., within one wave height from the waterline) in the unfrozen case gravel on the slope remolded to a much greater depth. The wave motion was adequate to move gravel on the entire slope but there was inadequate heat exchange below one wave height to promote melting.

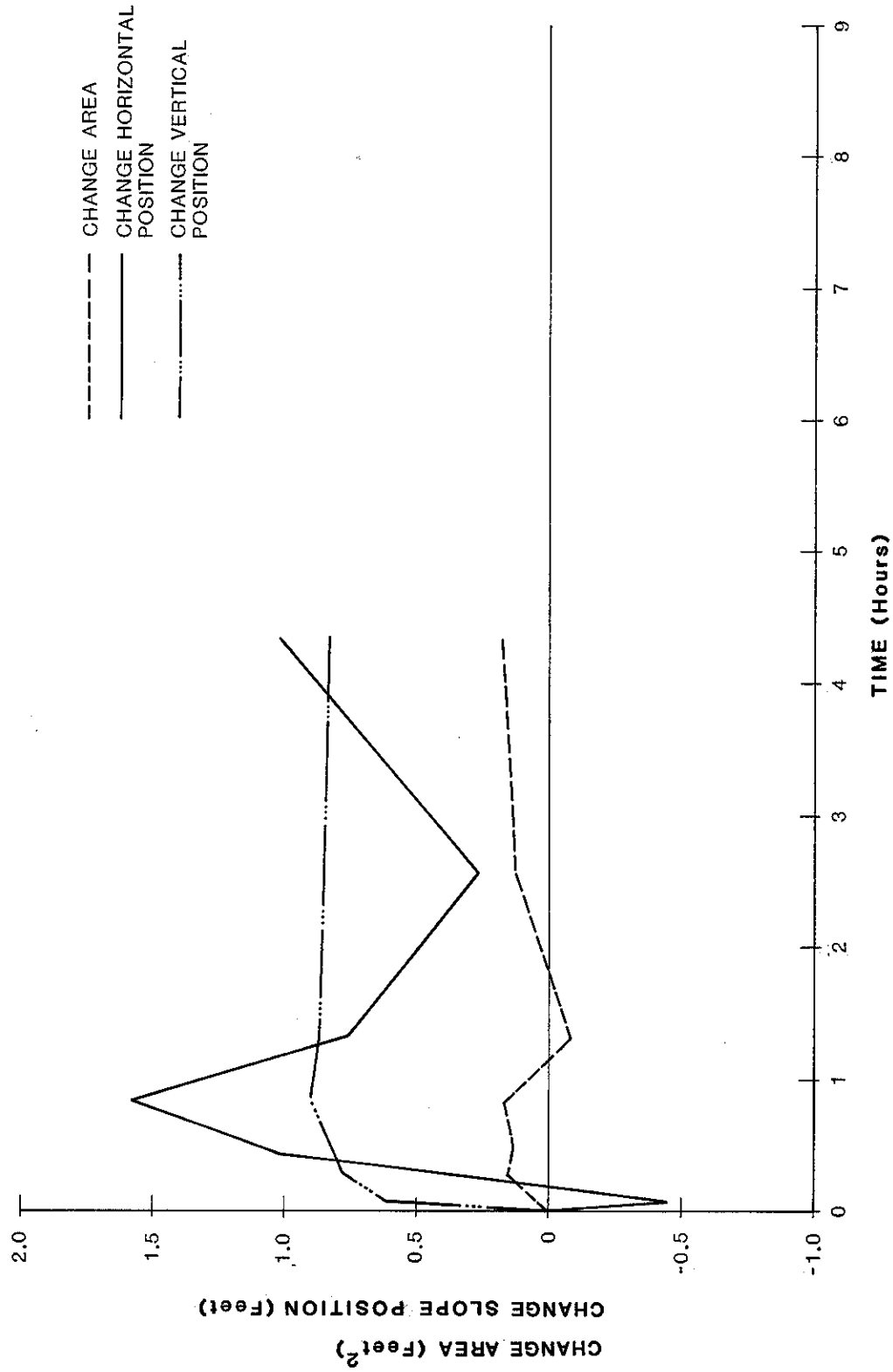


Figure 5.6
CHANGE IN AREA AND SLOPE DISPLACEMENT WITH TIME
(UNFROZEN SLOPE)

6. CONCLUSIONS AND RECOMMENDATIONS

The processes of erosion of a frozen versus an unfrozen gravel slope differ in one significant way. The frozen state of the soil does control and limit the erosion process. The depth of wave influence for heat exchange differs from the depth of wave influence for mobilization of loose gravel in a unfrozen berm. Therefore, the evolving slope profile also differs. Based on the experimental results of this program, an eroding frozen slope would be expected to ultimately develop a bench, roughly one wave height below the still waterline. An unfrozen slope would restabilize to a 1:7 slope.

Based on this limited test case, the need for slope protection might be questionable under attack by typical daily Beaufort Sea waves which are similar in size to those tested in this study. The frozen core appears to resist wave erosion, and its erosion rate can be predicted based on temperature difference and wave height. Considering a normal duration of an Arctic storm as three days, the frozen core should probably remain intact and not fail catastrophically. Substantial loss of unfrozen gravel on the slope above still water should still be expected but the advance of the erosion will be limited.

The setup of the model berm precluded examining the erosion and undercutting expected for a high steep slope or cliff. Also, these tests did not look at the case of a brine entrapped frozen berm. The presence of these unfrozen pockets might introduce a totally different erosion rate and process. Finally, the implications of overtopping and percolation through the unfrozen above water portion of the berm were not considered. Percolation may accelerate the melting of the frozen core, thus increasing the erosion rate.

Three major questions must be resolved before the erosion process can be assumed well defined:

1. Erosion of the unfrozen berm above still water level should be examined to see how undercutting and slope failure occur.
2. The erosion process of a frozen berm honeycombed with brine filled voids should be compared to the monolythic case.
3. Three-dimensional effects such as longshore transport of material should be considered in terms of the effect on the evolution of the eroded frozen slope.

It is recommended that these problems be addressed in the Phase II/III effort by conducting additional model tests and a field monitoring program. In these studies the erosion of an inhomogeneous frozen berm, representing a more realistic condition, can be examined.

7. REFERENCES

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ATTACHMENT B
14-12-0001-30209

U.S. DEPARTMENT OF THE INTERIOR
SMALL BUSINESS INNOVATION RESEARCH PROGRAM
PHASE I-FY 1984
DOI/SBIR 84-1
PROJECT SUMMARY

FOR DOI USE ONLY		
Program Office	Proposal No.	Topic No.

TO BE COMPLETED BY PROPOSER

Name and Address of Proposer

ARCTEC ENGINEERING, Incorporated
9104 Red Branch Road
Columbia, MD 21045

Name and Title of Principal Investigator

Jack C. Cox, Vice President

Title of Project

Wave Erosion of an Unprotected Frozen Gravel Berm

Topic

SubTopic

Technical Abstract (Limit to two hundred words)

This project examined the process of wave erosion of an unprotected frozen gravel berm. Using physical modeling techniques, the rate of erosion of the slope, the propagation of the freeze front within the berm, and the equilibrium beach profile were established. The results were compared against erosion of an identical nonfrozen berm. A mathematical expression for the erosion rate was developed. Preliminary findings suggest that the frozen core of a berm could be highly resistant to wave attack in the Arctic.

Keywords (8 max) Description of the Project, Useful in Identifying the Technology, Research Thrust and/or Potential Commercial Application

Gravel Berm, Permafrost Erosion, Thermal Erosion, Wave Erosion
Anticipated Results/Potential Commercial Applications of the Research

Depths of slope protection and need for slope protection are defined for wave degraded frozen gravel berms.